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FLAMMABILITY CHARACTERISTICS OF FIBER REINFORCED COMPOSITE MATERIALS

August 1990

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TECHNICAL REPORT

FLAMMABILITY CHARACTERISTICS
OF
FIBER REINFORCED COMPOSITE MATERIALS

by

A. Tewarson

Prepared for

U. S. Army Materials Technology Laboratory

405 Arsenal Street

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ABSTRACT

Fiber reinforced composite (FRC) materials are used extensively because of their physicochemical properties and high strength-to-weight ratio. The use of composites in U.S. Army vehicles, to decrease weight and enhance survivability, has been considered for some time. This report describes the results of a study undertaken by the Factory Mutual Research Corporation (FMRC) on FRC materials for possible composite combat vehicle applications on behalf of the U.S. Army Materials Technology Laboratory ~~(AMTL)~~. The objective of the study was to assess the flammability characteristics of FRC materials using small-scale experiments.

In the study, five FRC samples (about 3 to 45 mm in thickness) were examined. Results from the study showed that FRC materials have high resistance to ignition, a high heat of gasification and a low Fire Propagation Index (FPI), indicating that self-sustained fire propagation is expected to be difficult for these materials (fires are not expected to propagate beyond the ignition zone). Thus, these results suggest that FRC materials would not present as severe a fire hazard as ordinary combustibles; i.e., cellulosics and most plastics. Keywords: polymers, fire resistance. (JES)

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SUMMARY

This study was undertaken to assess the flammability characteristics of fiber reinforced composite (FRC) materials in terms of resistance to ignition and fire propagation, peak burning intensity and ease of fire extinguishment. Five materials (Table 1) were examined:

1. MTL #1: S-2 fiberglass polyester, non-flame retardant formulation, base line;
2. MTL #2: S-2 fiberglass/polyester, flame retardant, prepreg, formulated for the Army Materials Technology Laboratory (AMTL) by Owens-Corning Corporation;
3. MTL #3: S-2 fiberglass/polyester, flame retardant, prepreg, formulated for AMTL by American Cyanamide Corporation.
4. MTL #4: Aramid (Kevlar) phenolic-polyvinylbutyral (PVB), spall liner, formulated for AMTL by Russell Corporation.
5. MTL #5: S-2 fiberglass/phenolic, spall liner, formulated for AMTL by Owens-Corning Corporation.

The fire behavior of MTL #1, which is the baseline material and is of non-flame retardant formulation, is very different than the other samples as expected. This difference has been indicated in this report.

MTL #2 to #5 samples contained two-thirds by weight and 50% by volume of the noncombustible fiberglass.

Fiber: Resin Ratios (by weight)

MTL #1 - 70:30
MTL #2 - 70:30
MTL #3 - 70:30
MTL #4 - 84:16
MTL #5 - 80:20

All the experiments were performed in the FMRC's 50 kW-Scale Flammability Apparatus (Figure 1).

Result

For assessment of the fire hazards expected from the FRC materials, several fire properties associated with the following fire stages were quantified and compared with the fire properties of noncomposite materials (ordinary combustibles):

1. Ignition
2. Fire propagation
3. Steady state burning
4. Fire extinguishment.

1. Ignition

As materials are exposed to heat by various heat sources, vapors are generated. The vapors combine with air, forming combustible mixtures which auto ignite or are ignited by flames present in the neighborhood. This process is defined as ignition (auto or piloted) and is responsible for starting flaming fires. The ignition process is quantified in terms of two parameters:

a) Critical heat flux (or temperature) defined as the minimum heat flux (or temperature) below which the material cannot be ignited. Critical heat flux is expressed as kW/m^2 and temperature as °C (°F).

b) Thermal Response Parameter (TRP) defines the resistance to ignition and fire propagation. TRP is expressed as $kWs^{1/2}/m2$.

The critical heat flux and TRP values are quantified by measuring time to ignition at various external heat flux values. The higher the critical heat flux and TRP values, the higher the resistance to ignition and fire propagation. Thus materials (thicknesses of less than 5 mm) with TRP values of 300 $kWs^{1/2}/m^2$ or larger generally represent materials with high resistance to ignition and fire propagation. The following values were obtained for the FRC materials; for comparison, values for non-FRC materials from other FMRC studies are also listed.

a) <u>Critical Heat Flux in kW/m^2 and Temperature °C (°F)</u>

FRC	10-20; 355-478 (671-892)
Non-FRC	11-38; 390-631 (734-1169)

b) Thermal Response Parameter($kWs^{1/2}/m^2$)

FRC (3.2 to 4.8 mm thick)	338-610
Non-FRC (Polystyrene, 50 mm thick)	200
Non-FRC (PVC, 50 mm thick)	172
Non-FRC (Neoprene, 50 mm Thick)	154

The critical heat flux values for FRC and non-FRC materials are comparable, but the TRP for the FRC materials is higher, suggesting higher resistance to ignition and fire propagation than for the non-FRC materials.

2. Fire Propagation

After initiation, fire will propagate with burning proceeding over the surface and into the material. The fire hazard depends on the rate with which fire propagates. It is expressed in terms of the Fire Propagation Index (FPI) which is the ratio of the radiative heat release rate per unit width to the one-third power and the TRP. FPI is quantified by using a 24 in. (0.61 m) long and 4 in. (100 mm) wide vertical sheet in a 40% O_2 environment with bottom 8 in. (0.20 m) in the ignition zone (50 kW/m^2 of external heat flux exposure). Heat release rate is measured during fire propagation within and beyond the ignition zone.

The higher the FPI value, the higher the fire propagation rate. For materials with a thickness of less than 5 mm and FPI values of less than 10, fire propagation beyond the ignition zone is difficult. The following FPI values were determined for the FRC materials; for comparison, FPI value for a non-FRC material (polystyrene) is also listed:

FRC materials	FPI
MTL (#1; 4.8 mm thick)	13.3
MTL (#2 to #5; 3.2 tc 4.8 mm thick)	<10
Non-FRC (polystyrene, 50 mm thick)	30

The FPI values for FRC samples #2 to #5 suggest that self-sustained fire propagation beyond the ignition zone is not expected for these materials.

3. <u>Steady State Burning</u>

The fire intensity for the fully involved Sample is maximum. The hazard is presented by heat, fire products (toxic and corrosive) and smoke (reduced visibility), and depends on the generation rates of material vapors, fire products and heat release rate.

3.1 <u>Generation Rate of Material Vapors</u>

The important material properties which govern the generation rate of material vapors (mass loss rate) are:

a) Heat of gasification, defined as the amount of energy required to vaporize unit mass of the material. The higher the heat of gasification, the lower the generation rate of material vapors. Heat of gasification is expressed as kJ/g.

b) Surface reradiation loss. The higher the loss, the lower the generation rate of material vapors. The surface reradiation loss is very close to the critical heat flux value. The critical heat flux values are listed in the previous section.

c) Flame heat flux. The lower the flame heat flux value, the lower the generation rate of material vapors. The flame heat flux is expressed as kW/m^2.

The heat of gasification, surface reradiation loss and flame heat flux are used to assess the generation rate of material vapors (mass loss rate of the material). The following values were obtained for the FRC materials; values for non-FRC materials are included for comparison:

a) <u>Heat of Gasification (kJ/g)</u>

FRC materials	
MTL #3	2.9
MTL #1, 2, 4 and 5	5.1 to 7.8
Non-FRC (Polystyrene)	1.7
Non-FRC (Polyvinylchloride)	2.5
Non-FRC (Polypropylene)	2.0

b) Flame Heat Flux (kW/m^2)

FRC materials	
MTL #2, 4 and 5	20-21
MTL #3	37
MTL #1	51
Non-FRC (Polystyrene)	78
Non-FRC (Polypropylene)	71
Non-FRC (Polyvinylchloride)	50

c) Generation Rate of Material Vapors (Mass Loss Rate) in g/m^2s in Large-Scale Fires with an External Heat Flux of 60 kW/m^2

FRC materials	
MTL #5	8.2
MTL #4	8.5
MTL #2	12.9
MTL #1	15.8
MTL #3	30.0
Non-FRC (Polypropylene)	55.7
Non-FRC (Polyvinylchloride)	59.5
Non-FRC (Polystyrene)	73.5

The generation rate of vapors (mass loss rate) for FRC materials is significantly lower than it is for non-FRC materials within the external heat flux zone. It should be noted that for FRC materials #2 to #5, self-sustained fire propagation is not expected beyond the ignition zone.

3.2 Heat Release Rate

In a fire, heat is generated as a result of chemical reactions. Heat that is released in reactions where CO and CO_2 are generated, and O_2 is depleted, is defined as the chemical heat, and the rate as the chemical heat release rate. Chemical heat release rate is determined by measuring the generation rates of CO and CO_2 and the depletion rate of O_2 at various externally applied heat flux values. The ratio of the chemical heat release rate to the generation rate of materials vapors (mass loss rate) is defined as the chemi-

cal heat of combustion. The chemical heat of combustion is less than the net heat of complete combustion or the total heat of combustion as measured in the oxygen bomb calorimeter. The ratio of the chemical heat of combustion to the net heat of complete combustion is defined as the combustion efficiency of the material.

For fixed external and flame heat flux values and surface reradiation loss, the chemical heat release rate is governed by the ratio of the chemical heat of combustion to the heat of gasification, defined as the Heat Release Rate Parameter (HRP). The lower the HRP value, the lower the heat release rate.

The heat release rate can be calculated by multiplying HRP by the flame heat flux or the external heat flux minus the surface reradiation loss. The following HRP values were quantified for the FRC materials; values for non-FRC materials are also included for comparison. The chemical heat release rates calculated from HRP values are also listed below:

a) <u>Heat Release Rate Parameter (HRP)</u>

FRC MTL #1 to #5	1.6 - 3.2
Non-FRC (Polystyrene)	15.9
Non-FRC (Polypropylene)	19.0
Non-FRC (Douglas fir)	7.1
Non-FRC (Polyvinylchloride)	3.4

b) <u>Chemical Heat Release Rate in kW/m^2 for an External Heat Flux of 60 kW/m^2</u>

FRC MTL #1 to #5	98-282
Non-FRC (Polystyrene)	2000
Non-FRC (Polypropylene)	2150
Non-FRC (Polyvinylchloride)	340

The chemical heat release rate for the FRC materials within the external heat flux zone is significantly less than for the non-FRC materials.

3.3 Generation Rate of Fire Products

In fires, various types of products are generated. In this study generation rates of CO, CO_2, hydrocarbons, and smoke and light obscuration by smoke were quantified. The light obscuration of smoke is expressed in terms of mass optical density.

The ratio of the generation rate of a fire product to the generation rate of material vapors, or the mass loss rate, is defined as the yield of the product. For fixed external and flame heat flux values and surface re-radiation loss, the generation rate of a fire product is governed by the ratio of its yield to the heat of gasification of the material, defined as the Product Generation Parameter (PGP). The lower the PGP value, the lower the generation rate of the products.

The generation rates of the products can be calculated from PGP by multiplying it with the external and flame heat flux minus the surface reradiation.

The following data were obtained for CO and smoke for the FRC materials:

a) Product Generation Parameter (PGP)

FRC materials	CO	Smoke
MTL #2, 4 and 5	0.0032-0.0090	0.0032-0.011
MTL #1	0.0086	0.011
MTL #3	0.035	0.023
Non-FRC (Polypropylene)	0.012	0.029
Non-FRC (Polystyrene)	0.035	0.097
Non-FRC (Polyvinylchloride)	0.038	0.102

The CO and smoke PGP values for MTL #2, 4 and 5 are lower than the values for samples MTL #1 and 3 and the non FRC materials.

b) Mass Optical Density (MOD)

FRC materials	
MTL #4 and 5	0.07-0.27
MTL #1, 2 and 3	0.90-0.97
Non-FRC (Polypropylene)	0.55
Non-FRC (Polystyrene)	0.77
Non-FRC (Polyvinylchloride)	0.92

The lower the MOD values, the lower the light obscuration by smoke for a defined fire size. For FRC materials, the MOD values for MTL #4 and #5 are lower than the values for MTL #1, #2 and #3 and the non FRC materials.

4. Flame Extinguishment

In this study, flame extinguishment by Halon 1301 (with samples exposed to 60 kW/m^2 of external heat flux) was quantified. The following Halon 1301 concentrations in volume percent were found for flame extinguishment:

FRC materials	3.0 to 4.0
Non-FRC materials	2.6 to 4.0

The range is consistent with the design of the current suppression systems for the crew compartment where maximum acceptable concentrations are 6% by volume for 5 minutes or 10% by volume for 1 minute.

Conclusion

Within the FRC materials, MTL #1, which was the base line material, was not fire-retarded and the results from this study indicated that. In this report, the distinction has been made between MTL #1 and other MTL sample materials.

The results from this study suggest that FRC materials MTL #2 to #5 are expected to resist ignition and fire propagation; Samples #4 and #5 had the highest fire resistance. The higher resistance to ignition is due to higher # values of critical heat flux and thermal response parameter. The materials will burn within the ignition and external heat flux zones, but the generation rates of fire products and heat release rates are expected to be less than those for non-FRC materials such as polystyrene and polypropylene.

Halon 1301, with a concentration in the range of 3 to 4% by volume, is expected to extinguish flames from the burning FRC materials within the ignition and external heat flux zones with a flux up to 60 kW/m^2.

From the estimates based on results of this study performed at the Factory Mutual Research Corporation's Small Scale Flammability Apparatus, it can be concluded that a composite vehicle, by virtue of its construction, is not expected to present an unusual fire hazard. Such a conclusion, however, needs to be validated in larger scale fires, possibly using enclosures and/or parallel sheets made of the FRC materials.

Recommendations

It is recommended that the results from this study be validated in the large scale "field" tests that simulate realistic conditions.

I
INTRODUCTION

Fiber reinforced composite materials are used extensively because of their physicochemical properties, including high strength-to-weight ratio and excellent resistance to ballistic penetration by munition fragments. The use of composites in Army vehicles as a means of decreasing weight and enhancing survivability, without reducing personnel safety, has been under study for some time. The U.S. Army Materials Technology Laboratory (AMTL) has successfully demonstrated that a ground vehicle turret could be fabricated from FRC materials; since then the technology has been applied to the fabrication of a composite vehicle hull [1]. The U.S. Navy is also developing the use of FRC materials for numerous ship and submarine applications for Marine Corp amphibian armored personnel carriers, including use as major structural components. FRC materials are also finding extensive applications in the aerospace, automobile and other industries.

Although FRC materials are very attractive in terms of their physicochemical properties, concern for possible fire hazards is understandable as organic polymers are one of the major constituents of FRC materials (on the order of 30% by weight or 50% by volume). It is, therefore, important that the flammability of FRC materials be determined and compared with other materials.

This report describes the results for flammability characteristics evaluations of FRC materials using the FMRC Small-Scale Flammability Apparatus and the principles and techniques developed at FMRC.

II
GENERAL CONCEPTS

The flammability characteristics of a material are evaluated in terms of the following processes:

1. Ignition.
2. Fire propagation.
3. Generation of materials vapors, heat and fire products.
4. Fire suppression/extinguishment.

2.1 Ignition

As a material is subjected to heat source, vapors are generated which can be ignited by an ignition source such as a pilot flame. The time for generating vapors and ignition decreases as the heat flux received by the material increases. There is a minimum value of heat flux at or below which vapors are not generated and there is no ignition; this minimum heat flux is defined as the critical heat flux. The relationship between time-to-ignition and heat flux is used to define Thermal Response Parameter (TRP) (Eq. 4 in the Appendix) to characterize the ignition resistance and fire propagation behavior of materials. The higher the critical heat flux and TRP values, the greater the difficulty of initiating a fire, and the higher the resistance to fire propagation. Thus, for the assessment of fire hazard, ignition experiments are performed and critical heat flux and TRP values are determined from the experimental data for time-to-ignition measured at various external heat flux values [2-6].

2.2 Fire Propagation

After fire is initiated, it propagates away from the ignition source if sufficient heat is supplied to the material from either the flame of the burning material and/or the external heat sources. Fire propagation assisted by the flame heat flux from the burning material in the absence of external heat flux is defined as self-sustained fire propagation. The magnitude of the flame heat flux depends on the radiative component of the chemical heat release rate [4,6]. For materials with lower values of heat release rates and

higher values of TRP, self-sustained fire propagation is difficult; however, in the presence of external heat flux, fire propagation is sustained, but the fire propagation rate is low. For the quantification of fire propagation behavior of materials, a ratio of the radiative component of the chemical heat release rate and TRP is used (Eq. 13 in the Appendix). This ratio is defined as the Fire Propagation Index (FPI). Materials with low FPI values show that it is very difficult to create conditions for self-sustained fire propagation.

Fire propagation for FRC materials is expected to depend on the heat flux supplied to the material and ignition resistance of the material. Techniques have been developed for the quantification of fire propagation using FMRC's Small-Scale Flammability Apparatus [4,6] and the National Institute of Standards and Technology (NIST) Flame Spread Apparatus [11], which can be used for the FRC materials. Limiting Oxygen Index and its dependency on temperature has been used by AMTL to examine the fire propagation behavior of small samples of FRC materials [12].

2.3 Generation of Material Vapors

Upon ignition, the material starts burning and generates vapors, heat and fire products. The rate with which material vapors are generated is measured in terms of the mass loss rate of the material. The mass loss rate is measured at different heat flux values. The relationship between mass loss rate and heat flux is defined as the heat of gasification (Eqs. 1 to 3 in the Appendix). Heat of gasification is used to characterize the ease with which material vapors are generated. The higher the heat of gasification, the slower the rate of generation of material vapors and fire propagation.

2.4 Generation of Heat

The environments created in a fire are due to the generation of heat and fire products. The environment created in a fire as a result of generation of heat is defined as a thermal environment [17]. The environment created as a result of the generation of fire products is defined as a nonthermal environment [17].

The heat generated in a fire is due to various chemical reactions, the major contributors being those reactions where CO and CO_2 are generated, and O_2 is consumed [3]. The heat release rate thus is defined as the chemical

heat release rate [3]. Techniques are available to quantify chemical heat release rate using FMRC's Flammability Apparatus [2-6], Ohio State University (OSU) Heat Release Rate Apparatus [13] and the NIST Cone Calorimeter [14]. The chemical heat release rate has a convective and a radiative component [2]. Techniques are available to quantify the convective heat release rate using the FMRC Flammability Apparatus [2,3] and the OSU Heat Release Rate Apparatus [13]. The radiative heat release rate is the difference between the chemical and convective heat release rates [2,3].

2.5 Generation of Fire Products

The generation of products depends on the generic nature of the materials and additives, fire propagation rate, fire ventilation and fire mode (flaming and nonflaming). Techniques are available to quantify the generation of smoke, toxic and corrosive fire products using the NBS Smoke Chamber [15], pyrolysis-gas chromatography/mass spectrometry (PY-GC-MS) [16], FMRC Flammability Apparatus [2,3,5,17,18], OSU Heat Release Rate Apparatus [13] and the NIST Cone Calorimeter [14]. Techniques are also available to assess generation of: 1) toxic compounds in terms of animal response [19], and 2) corrosive compounds in terms of metal corrosion [17].

2.6 Fire Extinguishment

The extinguishment of fire depends on the fire propagation rate, physico-chemical properties of the materials, rate of application and the concentration of extinguishing agents. Water applied through sprinklers is the most widely used liquid extinguishing agent, and Halon 1301 and CO_2 are the most widely used gaseous agents. Techniques are available to quantify fire extinguishment in large-scale fires [20]; however, standardized small-scale techniques for quantifying fire extinguishment are practically nonexistent, although recently attempts are being made to develop them using FMRC's Small-Scale Flammability Apparatus [21].

2.7 Protection From Thermal and Non-Thermal Hazards

In order to reduce fire hazard, several procedures are used: 1) passive fire protection, such as materials with low FPI values, coatings, wrappings, physical separation using inert barriers, etc., and 2) active fire protection,

such as sprinklers, halon and other fire suppression and extinguishing agents. The effectiveness of the passive and active fire protection procedures is determined by performing burning and fire propagation experiments in the presence and absence of the respective agents.

Thus, in the flammability experiments designed for the assessment of hazard from thermal and nonthermal fire environments, the following parameters are quantified:

1) Critical heat flux, which is the minimum heat flux at or below which there is no ignition;

2) Thermal Response Parameter (TRP), which is related to the ignition temperature, thermal conductivity, density and specific heat of the material and represents the ignition and fire propagation resistance characteristic of the material;

3) Heat of gasification, which is the amount of energy required to vaporize a unit mass of the material initially at room temperature;

4) Heat of combustion, which is the amount of energy produced per unit mass of material burned. Energy produced when a unit mass of material burns completely is defined as the heat of complete combustion, and the energy produced when a unit mass of the material burns in fires is defined as the chemical heat of combustion. The chemical heat of combustion has a convective and a radiative component;

5) Yield of a fire product, which is the amount of the product produced per unit mass of the material vapors generated;

6) Mass optical density of smoke, which is the light obscuration (optical density) per unit mass of the material vapors generated per unit volumetric flow rate of the fire product air mixture;

7) Fire Propagation Index (FPI), which is the ratio of the radiative component of the chemical heat release rate and TRP.

These parameters are defined in detail in the Appendix.

III

EXPERIMENTS

Experiments were performed in the FMRC Small-Scale (50 kW) Flammability Apparatus shown in Figure 1, details of which are described in Refs. 5 and 6.

3.1 PROCEDURES

Horizontal, 0.10 x 0.10 m samples with edges covered tightly with heavy duty aluminum foil were exposed to external heat flux up to a maximum of 60 kW/m^2. A 0.01 m long ethylene-air premixed flame, located about 0.01 m from the surface, was used as a pilot flame for ignition. Ignition experiments were performed under natural air flow; all other experiments were performed under forced air flow conditions (velocity 0.2 m/s). The sample surfaces were coated with carbon black to eliminate differences in the surface absorptivity. In the experiments, the generation rate of material vapors was monitored by measuring the mass loss rate using a load cell. For the determination of heat release rate, generation rates of fire products and optical density of smoke, all the fire products were captured in the sampling duct along with air. In the duct, measurements were made for the total volumetric and mass flow rate of the fire product-air mixture, concentrations of CO, CO_2, hydrocarbons, smoke and O_2, optical transmission through smoke and gas temperature.

For the assessment of flame heat flux, $\dot{q}''_f$, expected in large-scale fires, 0.10 x 0.10 m, samples with edges covered tightly with heavy duty aluminum foil were burned in 40% oxygen concentration without the external heat flux [7]. Mass loss rate was measured and Eq. (3) in the Appendix was used to calculate $\dot{q}''_f$.

For the quantification of fire propagation behavior of the FRC materials, 0.10 m wide and 0.61 m long vertical sheets with thicknesses varying from 3 mm to 38 mm were used. The bottom 0.15 m of the sheet was exposed to 50 kW/m^2 of external heat flux in the presence of a 0.01 m long pilot flame to initiate fire propagation. For the simulation of large-scale flame radiation, experiments were performed in 40% oxygen concentration.

Fire extinguishment behavior of the FRC materials using Halon 1301 was quantified with a horizontal 0.01 x 0.01 m sample with edges covered tightly

with heavy duty aluminum foil. The sample surface was exposed to 60 kW/m^2 of external heat flux. Experiments were performed under forced air flow conditions, where Halon 1301 was added to the inlet air flow such that fire remained well ventilated.

3.2 MATERIALS

In the study, five materials listed in Table I were examined.

IV

RESULTS

4.1 IGNITION

The ignition data are listed in Table II and are plotted in Figures 2 and 3. In these figures it can be noted that Eq. (4) in the Appendix is satisfied, and thus from the inverse of the slope, the Thermal Response Parameter (TRP) is determined. Critical heat flux is also identified on the figure. With an increase in thickness, TRP value increases, as shown in Figure 4 for MTL #3 sample. The data for the critical heat flux and TRP for all the FRC materials examined in the study are listed in Table III. Critical heat flux values for non FRC materials such as Douglas fir (wood), polypropylene (PP) and polystyrene (PS)* are also included in the table for comparison. Ignition temperatures listed in the table are estimated from the critical heat flux values using the Stefan Boltzman law.

As can be noted, TRP values for FRC materials are higher than for non FRC materials. Thus FRC materials are expected to have higher resistance to ignition and propagation than the example non FRC materials.

4.2 MASS LOSS AND HEAT OF GASIFICATION

Figure 5 shows the average data for the peak mass loss rate as a function of the external heat flux. The data show that the mass loss rate is a linear function of the external heat flux, and Eq. (2) in the Appendix is therefore satisfied. The heat of gasification values thus have been determined from the inverse of the slopes of the lines. As can be noted from the slopes, the heat of gasification values for the FRC materials are higher than the value for wood. The heat of gasification values determined from the slopes are listed in Table III. Thus for a given heat flux, mass loss rate for FRC materials is expected to be less than the wood.

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* These materials are identified as example non-FRC materials in this report.

4.3 HEAT RELEASE RATE

Figure 6 shows a plot of average of peak chemical heat release rate as a function of external heat flux for the FRC materials. The rate is a linear function of external heat flux, and Eq. (9) in the Appendix is, therefore, satisfied. Thus, the ratio of chemical heat of combustion (ΔH_{Ch}) to heat of gasification, L, values for the FRC materials have been determined from the slope of the lines. The heat of combustion values have been determined from the ratio of the heat release rate to mass loss rate (Eq. (8)) in the Appendix. The values determined in this fashion are listed in Table III. As can be noted, there are some differences in the heat of combustion values determined from the generation rates of CO and CO_2 and depletion rate of O_2. For comparison, the heat of combustion values for wood, PP and PS are also included in the Table.

Thus for a given heat flux, the heat release rate for FRC materials is expected to be less than for PP&P's.

4.4 GENERATION RATE OF FIRE PRODUCTS AND MASS OPTICAL DENSITY OF SMOKE

In the experiments, generation rates of CO, CO_2, smoke and total gaseous hydrocarbons, depletion rate of O_2 and optical density of smoke were determined. As examples, Figures 7 and 8 show plots of generation rates of CO and smoke as functions of the external heat flux, where linear relationships can be noted as expected from Eq.(18) in the Appendix, and thus the ratios of the yields of CO and smoke to heat of gasification, Y_{CO}/L and Y_S/L, have been determined from the slopes. The yields of CO and smoke have been calculated from the ratios of the generation rates of the products to the mass loss rate (Eq. (16) of the Appendix). The yields of selected fire products for wood PP and PS are also included in Table III for comparisons.

Smoke generated in fires is responsible for reducing visibility, as well as damaging electrical components and equipments, discoloring materials and introducing unwanted odors on the materials. For the assessment of hazard due to reduction in visibility, optical density is quantified (Eq. 19 in the Appendix) and is expressed in terms of mass optical density (MOD) (Eq. 20 in the Appendix). The peak MOD values for the MTL Samples are shown in Figure 9 and are listed in Table III. For comparison, peak MOD values for wood, polypropylene and polystyrene are included in Table III.

Although MOD values for FRC and example non FRC materials are comparable, because of lower mass loss rate expected, less smoke is expected to be generated from FRC materials than from the example non FRC materials.

4.5 FIRE PROPAGATION

Fire propagation depends on the magnitude of the flame heat flux and TRP. As fire size increases, the radiative component of the flame heat flux increases. In the laboratory scale experiments, the increase in the radiative component of the flame heat flux is simulated by performing experiments in the presence of air with oxygen concentration greater than 21% [7]. As the oxygen concentration is increased, the radiative component of the flame heat flux increases [7]. It is thus expected that as oxygen concentration is increased, the fire propagation rate is expected to increase; this is shown in Figures 10 to 12 in terms of chemical heat release rate during fire propagation. For oxygen concentration values of 40% and greater, the flame heat flux reaches its asymptotic value expected in very large-scale fires [7]; Figure 13 shows a comparison of fire propagation behavior of the MTL samples in terms of chemical heat release rate at 40% oxygen concentration. The asymptotic flame heat flux values for MTL samples are listed in Table III. The fire propagation rate also depends on the TRP values. This is shown in Figure 14 for MTL # 3 sample, where fire propagation behavior of the sample with different thicknesses is expressed in terms of the chemical heat release rate. As thickness increases, TRP value increases (see Figure 4) and fire propagation rate decreases.

Figures 15 to 18 show the Fire Propagation Index (FPI) profiles for the MTL samples at 40% oxygen concentration. Peak FPI values are listed in Table IV and are shown graphically in Figure 19. Thus self-sustained fire propagation for FRC materials beyond the ignition zone is expected to be difficult with the exception of MTL #1.

4.6 FLAME SUPPRESSION/EXTINGUISHMENT BY HALON 1301

Halon 1301 is a gas and interacts with the flame chemistry resulting in flame suppression/extinguishment. The interaction with the flame chemistry results in the reduction of heat release rate and the flame heat flux; thus, the fire propagation rate is reduced as Halon is added to the air flow

entering the fire, as shown in Figures 20 and 21 for MTL #2 and #3 samples, respectively. In the experiments, the samples were exposed to 60 kW/m^2 of external heat flux in normal air. Different concentrations of Halon were added at different times for MTL #2 sample, until the flame was extinguished at 4%. For MTL #3 sample, the flame was extinguished at 2.5% of Halon. For both of these samples, the chemical heat release rate in the presence of Halon is less than the rate in the absence of Halon, i.e., there is fire instability even in the presence of 2% Halon. Thus, the rate of fire propagation is expected to be reduced. The flame extinguishment data obtained in this fashion for the MTL samples are listed in Table V. Minimum values of Halon 1301 for flame extinguishment reported in Reference 27 for other non-fiber reinforced composite materials are also included in Table V for comparison.

V

DISCUSSION

5.1 RESISTANCE TO IGNITION AND FIRE PROPAGATION

In this study, resistance to ignition and propagation was examined in terms of critical heat flux for ignition and the Thermal Response Parameter (TRP). Data for these parameters are listed in Table III. Figure 22 shows the TRP values for the FRC materials with thicknesses of 4.8 mm (3.2 mm for No. 5 Sample). In general, materials with thicknesses of about 5 mm with TRP values greater than about 300 $kW/s^{1/2}/m^2$, show high resistance to ignition and fire propagation. The FRC materials examined in this study satisfy these conditions and are expected to have high resistance to ignition and fire propagation.

5.2 HEAT RELEASE RATE

Heat release rate has been examined in terms of the ratio of heat of combustion to heat of gasification and the flame heat flux (Eq. (9) in the Appendix). The ratios are plotted in Figure 23 and the flame heat flux is plotted in Figure 24 for FRC and non-FRC materials. The heat of combustion, heat of gasification and flame heat flux for FRC materials are listed in Table III. In Figure 23, the ratios of the heat of combustion to heat of gasification within the FRC materials do not vary appreciably and are significantly lower than the ratios for the non-FRC materials, including wood. In Figure 24, the flame heat flux values for the FRC materials are significantly lower than the values for the non-FRC materials, with the exception of MTL sample #1. The flame heat flux values for the FRC materials are even lower than the values for the highly halogenated non-FRC materials. These data thus suggest that in large-scale fires heat release rates for FRC materials are expected to be significantly lower than the rates for non-FRC materials under similar values of exposure heat flux. Since the flame heat from a burning material for self-sustained fire propagation depends on the heat release rate, the self-sustained fire propagation is expected to be difficult for the FRC materials compared to the non-FRC materials. Also, hazards from thermal fire environments are expected to be significantly less for the FRC materials than for the non-FRC materials.

5.3 SELF-SUSTAINED FIRE PROPAGATION

The self-sustained fire propagation for the FRC materials has been quantified in terms of the Fire Propagation Index (FPI). The profiles of the FPI values quantified for 0.10 m wide and 0.61 m long vertical sheets of the FRC materials are shown in Figures 15 to 18 and the peak FPI values are listed in Table IV and shown in Figure 19. A comparison of FPI values for the FRC materials with values for cables [6], as listed in Table IV, suggests that the FPI values for FRC materials, with the exception of MTL #1, are comparable to the FPI values for Group 1 cables for which self-sustained fire propagation is not expected beyond the ignition zone.

The fire propagation behavior can also be assessed on the basis of the rate of fire propagation calculated from Eq. (14) in the Appendix and the flammability data, as listed in Table III. A comparison between calculated rate of fire propagation and Fire Propagation Index is shown in Figure 25, where a good correlation can be noted.

5.4 HAZARDS DUE TO THERMAL AND NONTHERMAL FIRE ENVIRONMENTS

For FRC materials, the generation heat and fire products are expected to be limited to the burning in the ignition zone. For relative comparisons of heat release rates and generation rates of fire products and light obscuration, the ratios of heat of combustion to heat of gasification, as shown in Figure 23, the yield of individual fire products to heat of gasification and the mass optical density to heat of gasification (data listed in Table III), are useful. Under similar heat flux in the ignition zone, the ratios suggest that for FRC materials, heat release rates, generation rates of fire products and light obscuration by smoke are expected to be significantly lower than for the non-FRC materials. For non FRC materials considered in this report for comparison, fire is expected to propagate beyond the ignition zone, and the rates and light obscuration are expected to increase further.

5.5 FIRE SUPPRESSION/EXTINGUISHMENT BY HALON 1301

As discussed previously, for FRC materials, the fire propagation is expected to be limited to the ignition zone. Thus, fire suppression/ extinguishment by Halon 1301 showed to be effective in this zone. In this study, fire suppression/extinguishment experiments using Halon 1301 were performed

with FRC samples exposed to 60 kW/m^2, a very strong ignition source. As shown in Figures 20 and 21, the heat release rate decreases in the presence of Halon 1301, suggesting that combustion efficiency is decreased. This is supported by the data for the yield of CO and chemical heat of combustion for MTL samples #1 to #4 as examples in Figures 26 and 27, respectively. The yield of CO increases and heat of combustion decreases with an increase in the halon concentration until flame extinguishment. The data reported in Table V for Halon 1301 concentration required for flame extinguishment vary in the range of 3 to 4%, which is comparable to the range found for ordinary combustibles. Thus maintenance of Halon 1301 concentrations in excess of 4% is expected to extinguish fires in the ignition zone for the FRC materials; this concentration limit satisfies the current Halon 1301 requirements for fire suppression systems for tracked vehicles.

VI
CONCLUSION

Within the FRC materials, MTL #1, which was the base line material, was not fire-retarded and the results from this study indicated that. In this report, the distinction has been made between MTL #1 and other MTL sample materials.

The results from this study suggest that FRC materials MTL #2 to #5 are expected to resist ignition and fire propagation; Samples #4 and #5 had the highest fire resistance. The higher resistance to ignition is due to higher # values of critical heat flux and thermal response parameter. The materials will burn within the ignition and external heat flux zones, but the generation rates of fire products and heat release rates are expected to be less than those for non-FRC materials such as polystyrene and polypropylene.

Halon 1301, with a concentration in the range of 3 to 4% by volume, is expected to extinguish flames from the burning FRC materials within the ignition and external heat flux zones with a flux up to 60 kW/m^2.

From the estimates based on results of this study performed at the Factory Mutual Research Corporation's Small Scale Flammability Apparatus, it can be concluded that a composite vehicle, by virtue of its construction, is not expected to present an unusual fire hazard. Such a conclusion, however, needs to be validated in larger scale fires, possibly using enclosures and/or parallel sheets made of the FRC materials.

VII

RECOMMENDATIONS

It is recommended that the results from this study be validated in the large scale "field" tests that simulate realistic conditions.

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NOMENCLATURE

A	Total surface area of the material involved in fire (m^2)
c_p	Specific heat (kJ/g K)
c_j	Concentration (volume %)
$\dot{C}''_{O_2}$	Mass consumption rate of O_2 (g/m^2s)
D	Optical density (m^{-1})
f_j	Generation efficiency (-)
FPI	Fire propagation index
FRC	Fiber reinforced composite
$\dot{G}''_j$	Generation rate per unit area (g/m^2s)
ΔH_i	Heat of combustion (kJ/g)
I/I_o	Fraction of light transmitted (-)
k	Thermal conductivity (kW/mK)
k_j	Maximum possible theoretical yield (g/g)
k_{O_2}	Mass oxygen-to-fuel stoichiometric ratio (g/g)
ℓ	Optical path length (m)
L	Heat of gasification (kJ/g)
MOD	Mass optical density (m^2/g)
$\dot{m}''$	Mass loss rate per unit surface area (g/m^2s)
M_{O_2}	Mass fraction of oxygen
M	Total mass flow rate of fire products-air mixture (g/s)
$\dot{q}''$	Heat flux per unit surface area (kW/m^2)
$\dot{Q}''$	Heat release rate per unit surface area (kW/m^2)
$\dot{Q}'_i$	Heat release rate per unit width or circumference (kW/m)
ΔT	Temperature above ambient (°K)
t	Time (s)
TRP	Thermal Response parameter ($kWs^{1/2}/m^2$)
$\dot{V}$	Total volumetric flow rate of fire products-air mixture (m^3/s)
V	Fire propagation rate (mm/s)
Y_j	Yield (g/g)
ρ	Density (g/m^2)
χ_i	Combustion efficiency (-)
δ_f	Effective flame heat transfer distance (m)

Subscripts

Ch	Chemical
Con	convective
Cr	Critical
CO	Carbon monoxide
e	External
f	Flame
g	Gas
i	Chemical, convective or radiative
ig	Ignition
j	Fire product
n	Net
rr	Surface reradiation loss
R	Radiative
S	Smoke
T	Net heat of complete combustion

Superscripts

•	Per unit of time (s-1)
'	Per unit width or circumference (m-1)
"	Per unit surface area of the material (m^{-2})

TABLE I

FIBER REINFORCED COMPOSITE MATERIALS USED IN THE STUDY

Properties of S-2 Glass Fibers

Density	2.49 g/cm^3	0.09 lbs/cu. in.
Tensile Strength	45,818 MPA	665 KSI
Mod of Elasticity	86.81 GPA	12.6 MSI
Ult. Elongation	5.4% @ 72 F	
Filament Type & Size	Magnesia aluminosilicate fiber of G filament diameter (0.00036 in.)	

S-2 Glass Woven Fabric Description

Designation	(S-2 Glass, 250AA463 5x5.12 PW) 24 oz/sq yd, 5x5.12 plain weave, 463 semi-compatible fiber finish

MTl #1 (S-2/polyester, MTL base line)

Resin - Owens Corning Fiberglas (OCF) E-701, unpromoted, non-thixotropic isophthalic polyester resin, 35-40% styrene monomer, no flame retardant additive.

Glass - S-2 Glass, 250AA463 5x5.12 PW

Hand layup using 1-2% MeKP and .02% CoNP.

Thickness: 4.8 mm

Fiber resin ratio: 70:30 (by weight)

MTl #2 (S-2/polyester, Owens Corning Prepreg)

Resin - Owens Corning Fiberglas (OCF) E-780, unpromoted, non-thixotropic isophthalic polyester resin, specifically developed and formulated for ballistic applications, 35-40% styrene monomer. Resin system is custom compounded for flame retardancy and thick laminate moldability. Formulation taken from 85-0006.

TABLE I

FIBER REINFORCED COMPOSITE MATERIALS USED IN THE STUDY
(continued)

Resin	Isophthalic Polyester
Additive	DAP (diallyl phthlate)
Filler	SB-332 (aluminum trihydrate)
Additive	Glycerine
Catalyst	TBPB (tertiary butyl perbenzoate)
	L-256 (dimethyl hexane)
Thickener	PG 9104 (calcium hyroxide disp.)

Glass - S-2 glass, 250AA463 5x5.12 Pw

Prepreg layup, vacuum bag molding, elevated temperature cure.

Thickness; 4.8 mm

Fiber to resin ratio: 70:30 (by weight)

MTL #3 (S2/polyester, American Cyanamid Prepreg)

Company Designation - CYCOM 4102-5x5 WOV. S-Glass-48"

Resin - CYCOM 4102 Structural Polyester Resin, diallyl phthalate monomer, peroxide cure, antimony trioxide additive 1-3%.

Glass - S-2 Glass, 250AA463 5x5.12 PW

Vacuum Bag Molded, 170 F cure, 250 F Post Cure

Laminates must conform to MIL-L-46197(MR), LAMINATE: S-2 GLASS, FABRIC-REINFORCED, POLYESTER RESIN PREIMPREGNATED, DATED 23 DECEMBER 1987

Thickness: 4.8, 19 and 45 mm

Fiber to resin ratio: 70:30 (by weight)

MTL #4 (Kevlar/Phenolic-PVB, Russell Plastics)

Laminates must conform to MIL-L-62474 B (AT), LAMINATE: ARAMID-FABRIC-REINFORCED, PLASTIC, DATED 25 JANUARY 1984.

Thickness: 4.8 mm

Fiber to resin ratio: 84:16 (by weight)

TABLE I

FIBER REINFORCED COMPOSITE MATERIALS USED IN THE STUDY
(continued)

MTL #5 (S2/Phenolic Armor, Owens Corning Fiberglas)

Resin: Resole phenolic solution from Borden Chemical designation SC1008

60-66% by weight solids
25% isopropyl alcohol, free solvent
10-16% free phenol
1% free formaldehyde

Glass - S-2 Glass 250AA463 5x5.12 PW

Prepreg layup, press molding

Laminates shall conform to MIL-L-64154, LAMINATE: FIBERGLASS-FABRIC-REINFORCED, PHENOLIC.

Thickness: 3.2 m

Fiber to resin ratio: 80:20 (by weight)

TABLE II

PILOTED IGNITION DATA

Sample: MTL #1 S-2/Polyester MTL Baseline (E-701), 4.8 mm Thick

Heat Flux (kW/m^2)	Time to Ignition (s)
30	156.6
40	90.8
50	59.1
60	41.0
25	233.6
20	333.4
15	823.4
10	Did not ignite (900)

Sample: MTL #2 S-2/Polyester Owens-Corning Prepreg, 4.8 mm Thick

Heat Flux (kW/m^2)	Time to Ignition (s)
30	124.7
40	82.5
50	57.2
60	40.1
20	317.5
15	Did not ignite (900)

Sample: MTL #3 S-2/Polyester American Cyanamide Prepreg, 4.8 mm Thick

Heat Flux (kW/m^2)	Time to Ignition (s)		
	4.8 mm	19 mm	45 mm
30	121.4	286.0	530.0
40	68.7	144.1	243.0
50	48.3	92.2	138.9
60	32.4	57.7	87.7
25	-	411.7	-
20	291.0	-	-
15	623.2	-	-
10		Did not ignite (900)	

TABLE II

PILOTED IGNITION DATA

(Continued)

Sample: MTL #4 Kevlar/Phenolic-PVB Russell Corp. Spall Liner, 4.8 mm Thick

Heat Flux (kW/m^2)	Time to Ignition (s)
30	143.0
40	84.2
50	57.2
60	40.7
20	295.8
15	Did not ignite (900)

Sample MTL #5 S-2 Phenolic Owens-Corning Spall Liner, 3.2 mm Thick

Heat Flux (kW/m^2)	Time to Ignition (s)
30	365.1
40	170.0
50	89.1
60	57.2
20	Did not ignite (900)

TABLE III

FIRE PROPERTIES OF FIBER REINFORCED COMPOSITE MATERIALS

Sample No.	Material	Critical Heat Flux for Ignition (kW/m²)	Ignition Temperature °C (°F)	Thermal Response Parameter (kWs²/m²)	Heat of Gasification (kJ/g)	Flame Heat Flux[a] (kW/m²)	External Heat Flux (kW/m²)	Residue (% of Initial Weight)	Chemical Heat of Combustion (kJ/g) From CO & CO_2	Chemical Heat of Combustion (kJ/g) From O_2	Yield (g/g) CO	Yield (g/g) CO_2	Yield (g/g) O_2[b]	Yield (g/g) Sm	Yield (g/g) CH[c]	Mass Optical Density (m²/g)
MTL #1	S-2/Polyester (MTL Base line, E-731)	10	355 (671)	382	3.4	51	30	63	17.7	18.5	0.050	1.40	1.47	0.070	0.0086	0.932
							45	63	17.7	17.6	0.058	1.45	1.44	0.068	0.0060	0.897
							60	62	17.9	18.0	0.053	1.47	1.48	0.073	0.0071	1.070
							Average	63	17.9		0.055	1.47	1.44	0.070	0.0072	0.966
MTL #2	S-2/Polyester (Owens-Corning Prepreg.)	15	424 (796)	406	5.1	21	30	68	15.0	18.1	0.042	1.23	1.48	0.051	0.0055	0.809
							45	67	15.6	15.1	0.038	1.28	1.24	0.051	0.0030	0.804
							60	67	14.6	17.3	0.037	1.20	1.42	0.059	0.3031	1.080
							Average	67	16.0		0.039	1.24	1.38	0.054	0.0039	0.898
MTL #3	S-2/Polyester (American Cyanamide Prepreg.)	10	355 (671)	338[1] 417[2] 476[3]	2.9	37	30	69	7.9	9.0	0.122	0.650	0.741	0.066	0.020	0.874
							45	70	9.0	9.7	0.085	0.738	0.793	0.066	0.018	0.960
							60	69	9.0	11.0	0.099	0.741	0.903	0.072	0.018	1.03
							Average	69	9.3		0.102	0.710	0.812	0.068	0.019	0.955
MTL #4	Kevlar/Phenolic PVB (Russell Corp Spall Liner)	15	424 (796)	403	7.8	21	30[d]	24	11.9	—	0.021	1.06	—	0.019	0.0019	0.175
								4526	15.4	14.1	0.031	1.25	1.22	0.034	0.0021	0.550
							60	24	14.4	15.3	0.018	1.29	1.32	0.046	0.0012	0.790
							Average	25		14.8	0.025	1.27	1.27	0.041	0.0017	0.0670
MTL #5	S-2/Phenolic (Owens Corning Spall Liner)	20	478 (892)	610	7.3	20	30[e]	—	—	—	—	—	—	—	—	—
							45	91	12.5	—	0.075	1.08	—	0.027	0.0027	0.207
							60	90	10.2	13.1	0.057	0.88	1.04	0.019	0.0024	0.332
							Average	91	11.9		0.066	0.98	1.04	0.023	0.0026	0.270
	Douglas fir	11	390 (734)	—	1.82	—	—	—	13.0		0.004	1.31	—	0.015	0.001	0.092
	Polypropylene	18	478 (892)	—	2.03	71	—	—	38.6		0.024	2.79	—	0.059	0.007	0.553
	Polystyrene	13	419 (786)	—	1.70	78	—	—	27.0		0.060	2.33	—	0.164	0.014	0.771

a: For combustion in normal air with a sample area of about 0.01 m², exposed to external heat flux in the range of 30 to 60 kW/m².
b: Depletion yield.
c: CH represents total gaseous hydrocarbons.
d: Not used in averaging.
e: Heat flux not used.
1: Thickness 4.8 mm; 2: Thickness 19 mm; 3: Thickness 45 mm.

TABLE IV

PEAK FIRE PROPAGATION INDEX VALUES FOR FIBER REINFORCED COMPOSITE MATERIALS

Sample No.	Thickness (mm)	Peak FPI
MTL #1	4.8	13.3
MTL #2	4.8	ND
MTL #3	4.8	9.7
	19	7.8
	45	6.6
MTL #4	4.8	7.8
MTL #5	3.2	3.2
Fluorinated Ethylene-Propylene Cable[a]	-	5.0
PE/PVC Cable[b]	-	20

[a]No self-sustained fire propagation; classified as Group 1 cable (FPI <10) [6];

[b]Very rapid self-sustained fire propagation; classified as Group 3 cable (FPI ≥ 20) [6];

ND: Not determined.

TABLE V

VOLUME % OF HALON 1301 REQUIRED FOR FLAME EXTINCTION

Sample No.	Volume (%)
MTL #1[a]	4.0
MTL #2[a]	4.0
MTL #3[a]	3.0
MTL #4[a]	4.0
MTL #5[a]	3.5
Wood[b]	4.0
Polypropylene	4.0
Polyethylene[b]	3.9
Polystyrene[b]	3.9
Polyvinylchloride[b]	2.6

a: Fiber reinforced composite materials examined in this study. 0.01 x 0.01 m samples exposed to 60 k/W/m^2 of external heat flux.

b: Data reported by various authors compiled in Ref. 27. Experimental conditions are not defined.

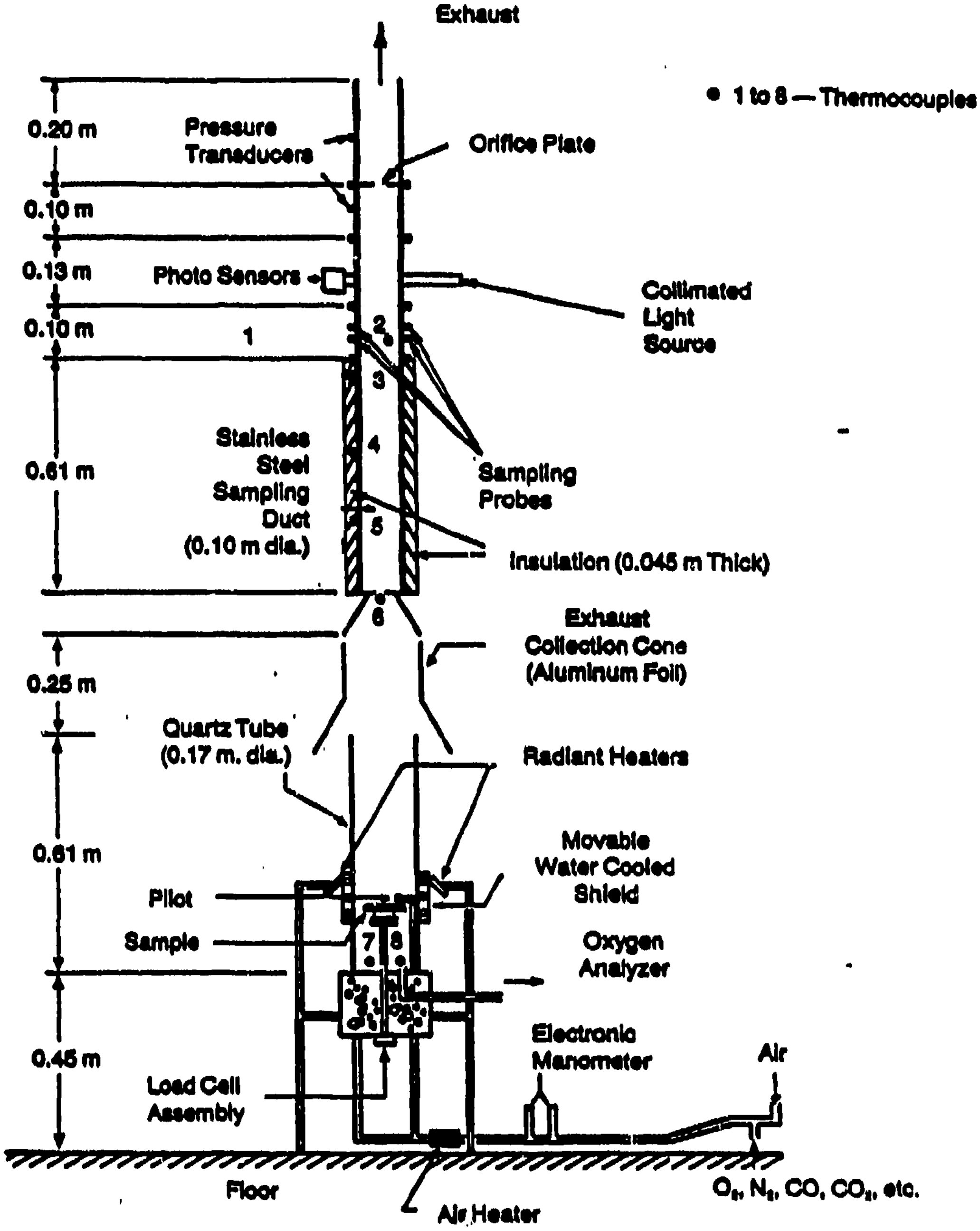

Figure 1. FMRC's Small Scale (50 kW) Flammability Apparatus.

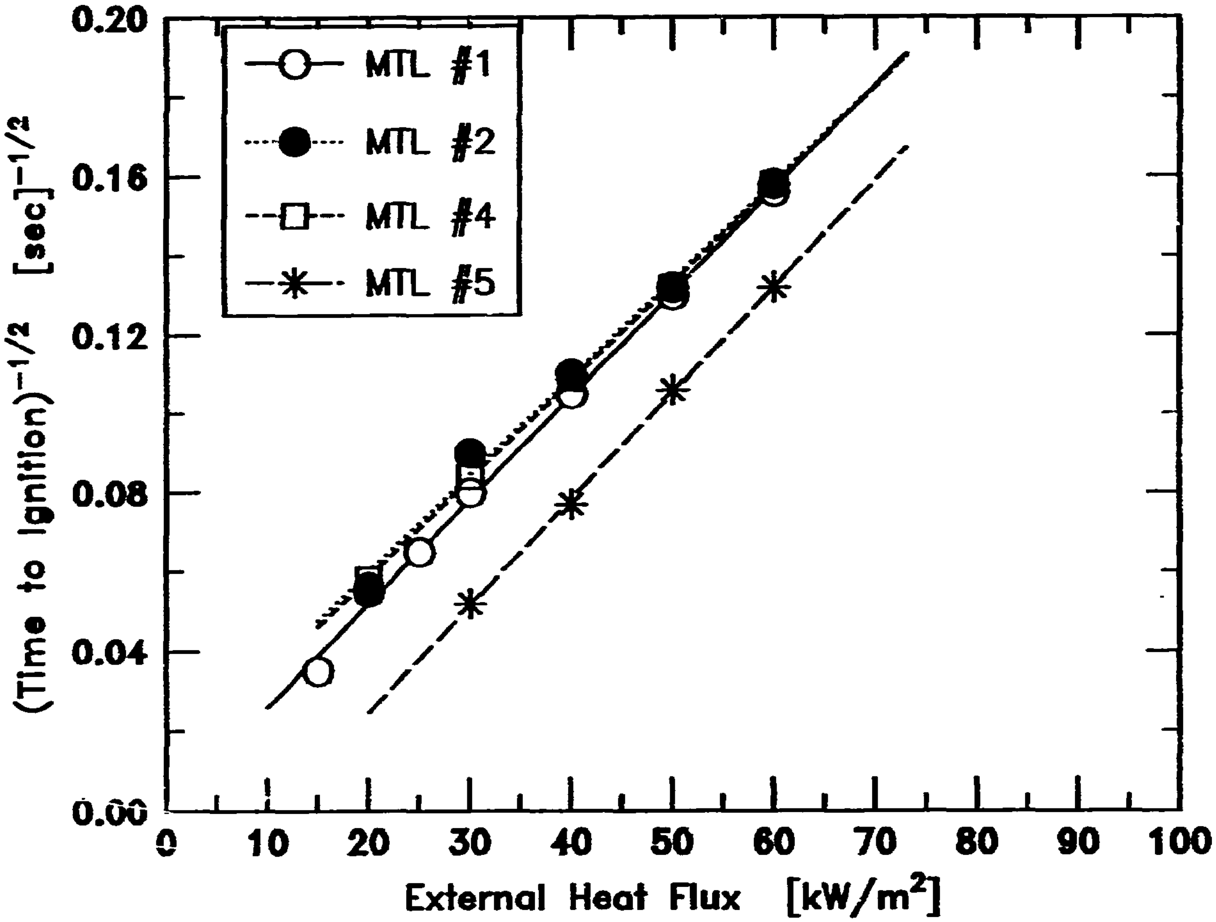

Figure 2. Piloted Ignition Data for Fiber Reinforced Composite Materials.

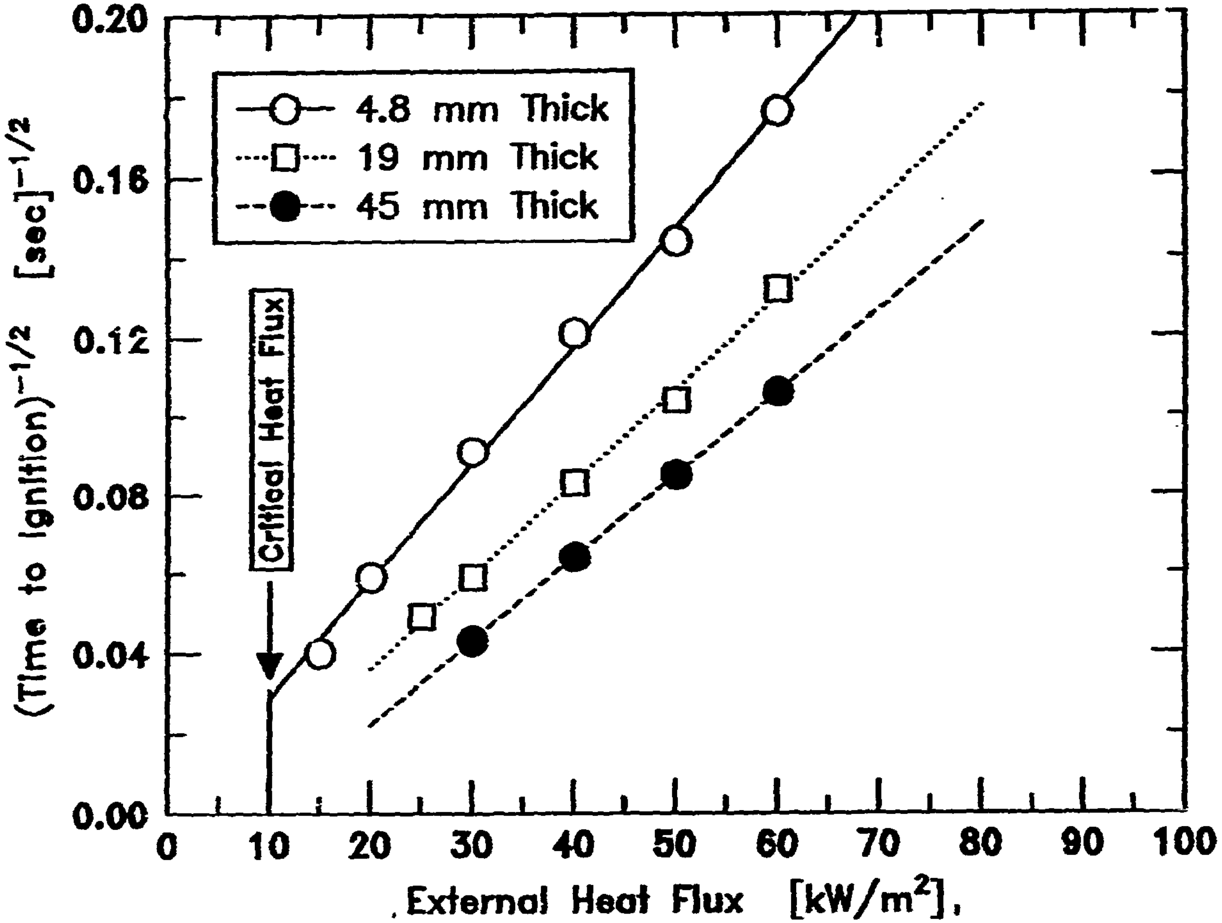

Figure 3. Piloted Ignition Data for S-2/Polyester; MTL #3 (American-Cyanamide Prepreg). TRP = 333, 417 and 476 kWs$^{1/2}$/m^2 for 4. 8, 19 and 45 mm thick samples, respectively.

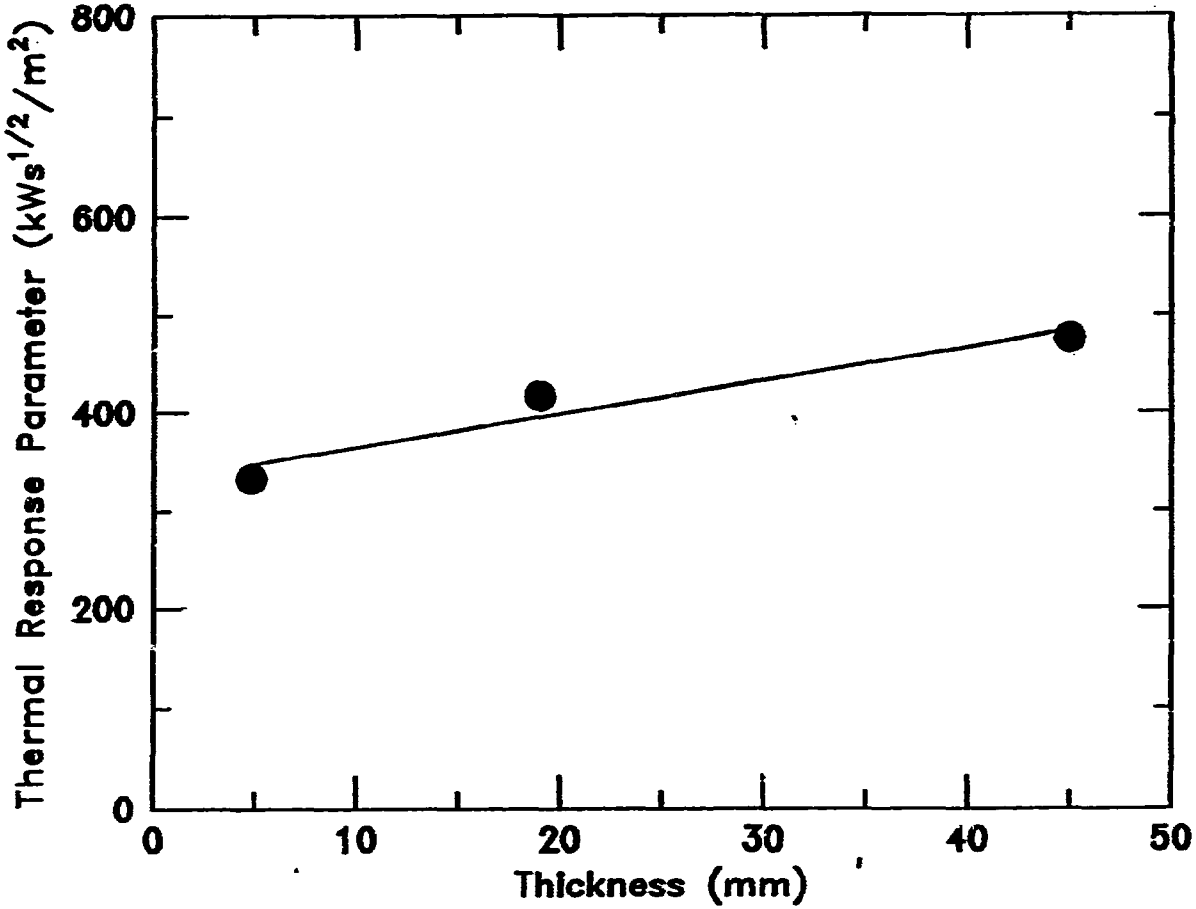

Figure 4. Thermal Response Parameter as a Function of Thickness for S-2/Polyester; MTL #3 (American-Cyanamide Prepreg).

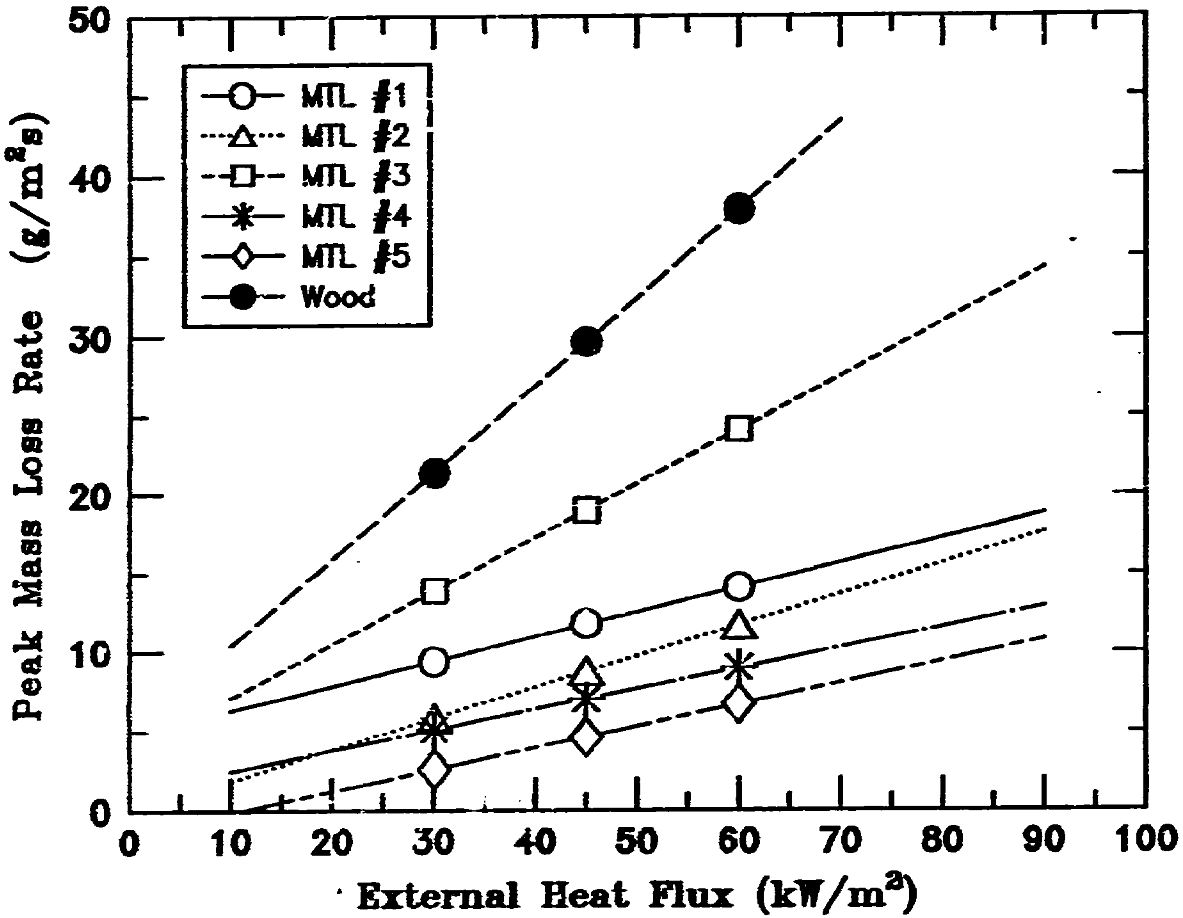

Figure 5. Peak Mass Loss Rate as a Function of External Heat Flux for Fiber Reinforced Composite Materials. Data for wood are Included for Comparison.

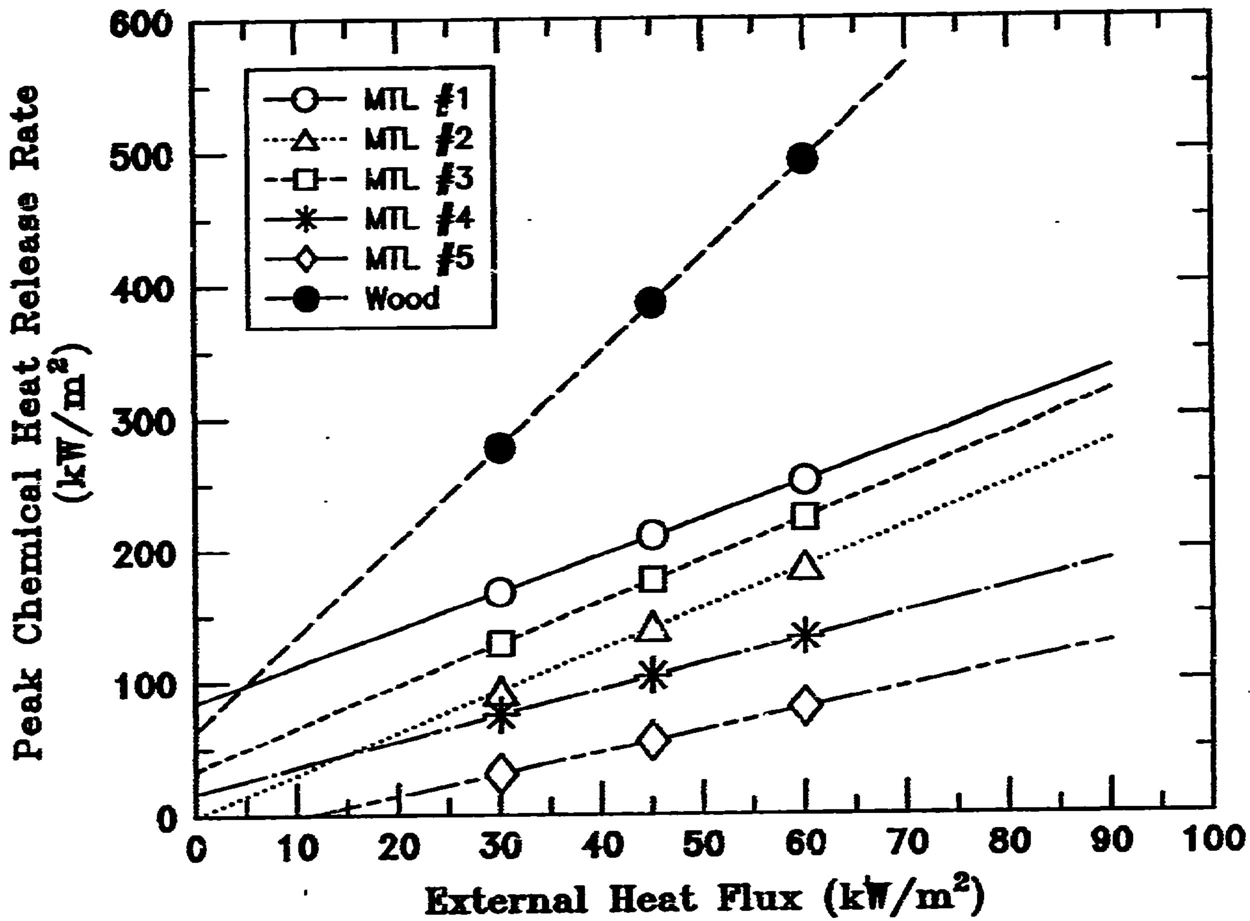

Figure 6. Peak Chemical Heat Release Rate as a Function of External Heat Flux for Fiber Reinforced Composite Materials. Data for Wood are Included for Comparison.

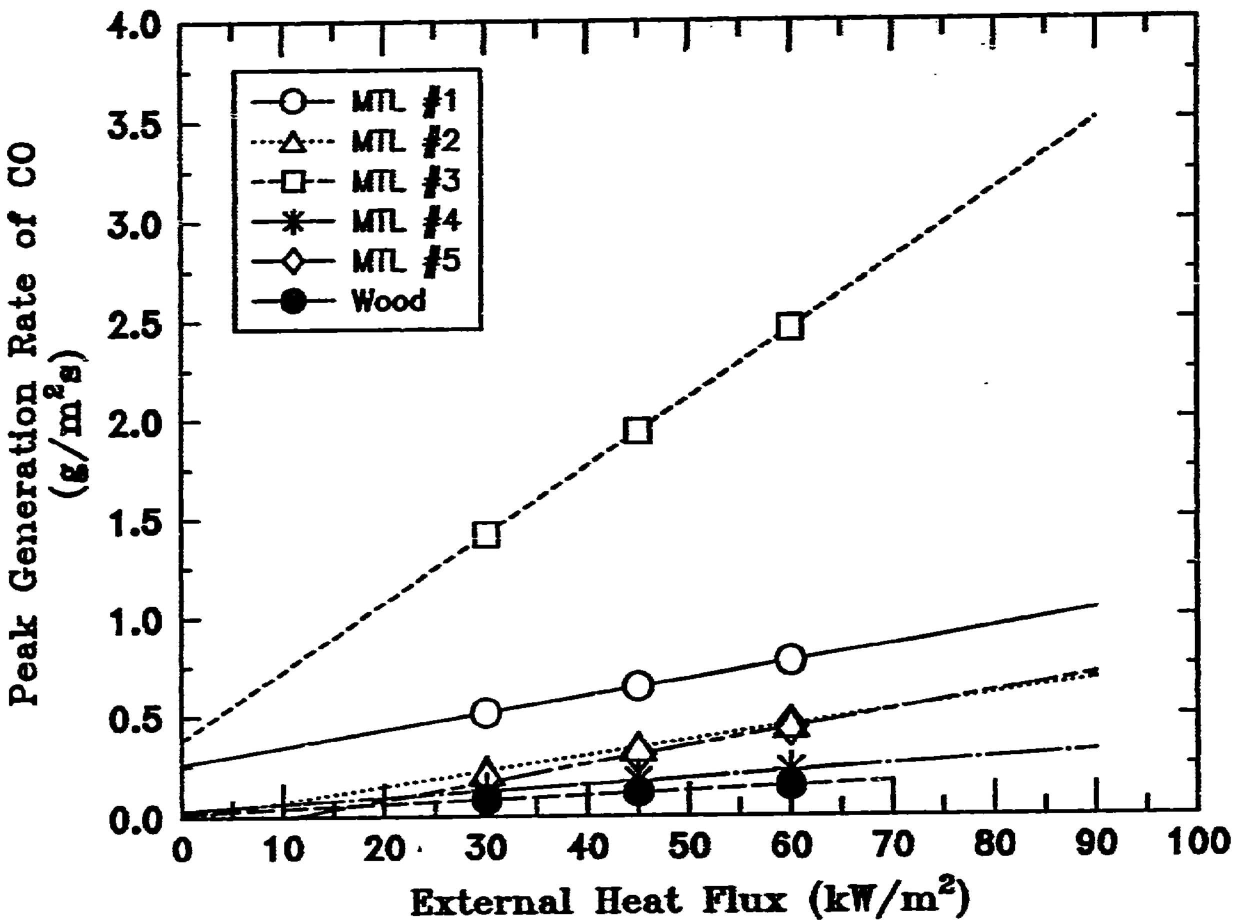

Figure 7. Peak Generation Rate of Carbon Monoxide as a Function of External Heat Flux for Fiber Reinforced Composite Materials. Data for Wood are Included for Comparison.

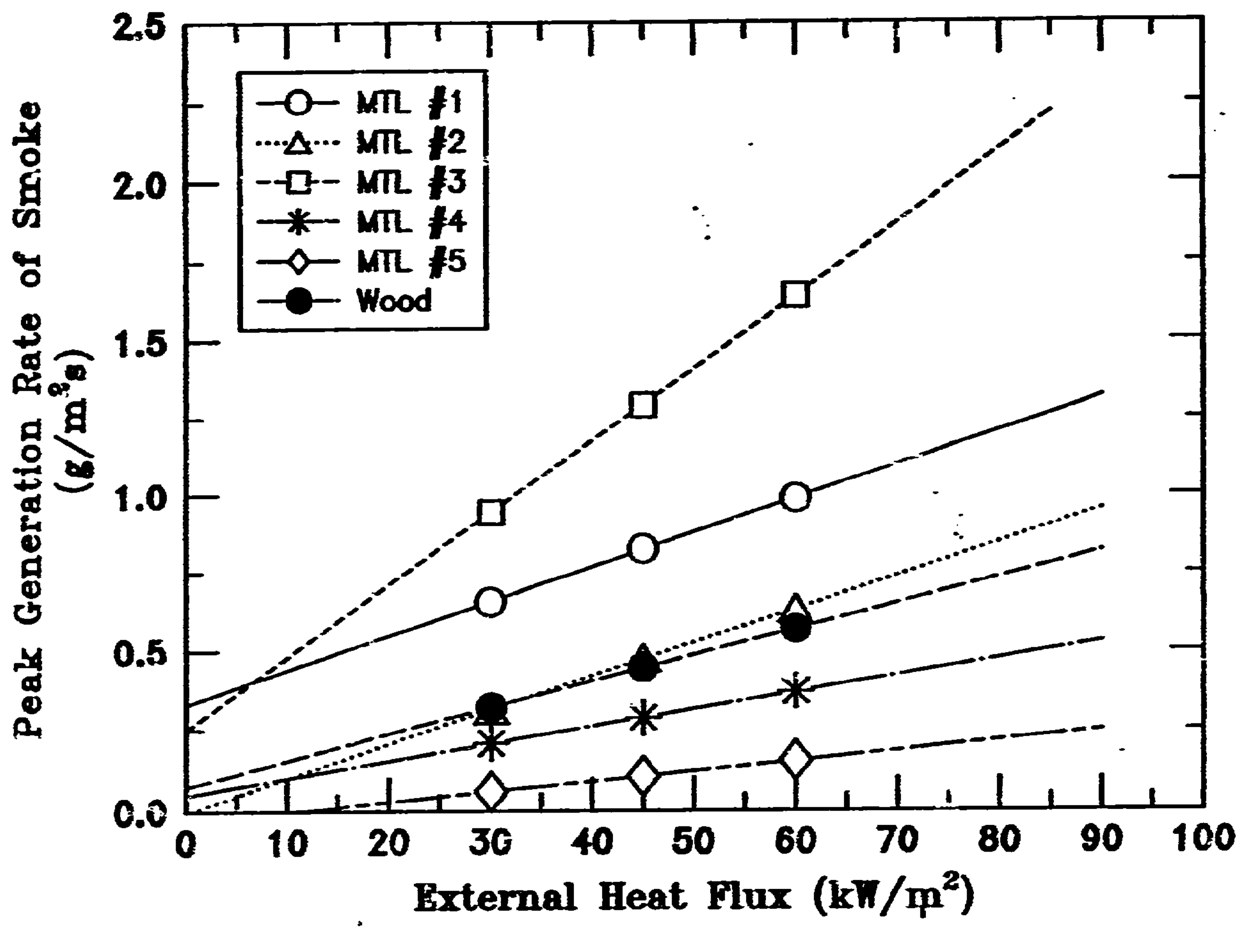

Figure 8. Peak Generation Rate of Smoke as a function of External Heat Flux for Fiber Reinforced Composite Materials. Data for Wood are Included for Comparison.

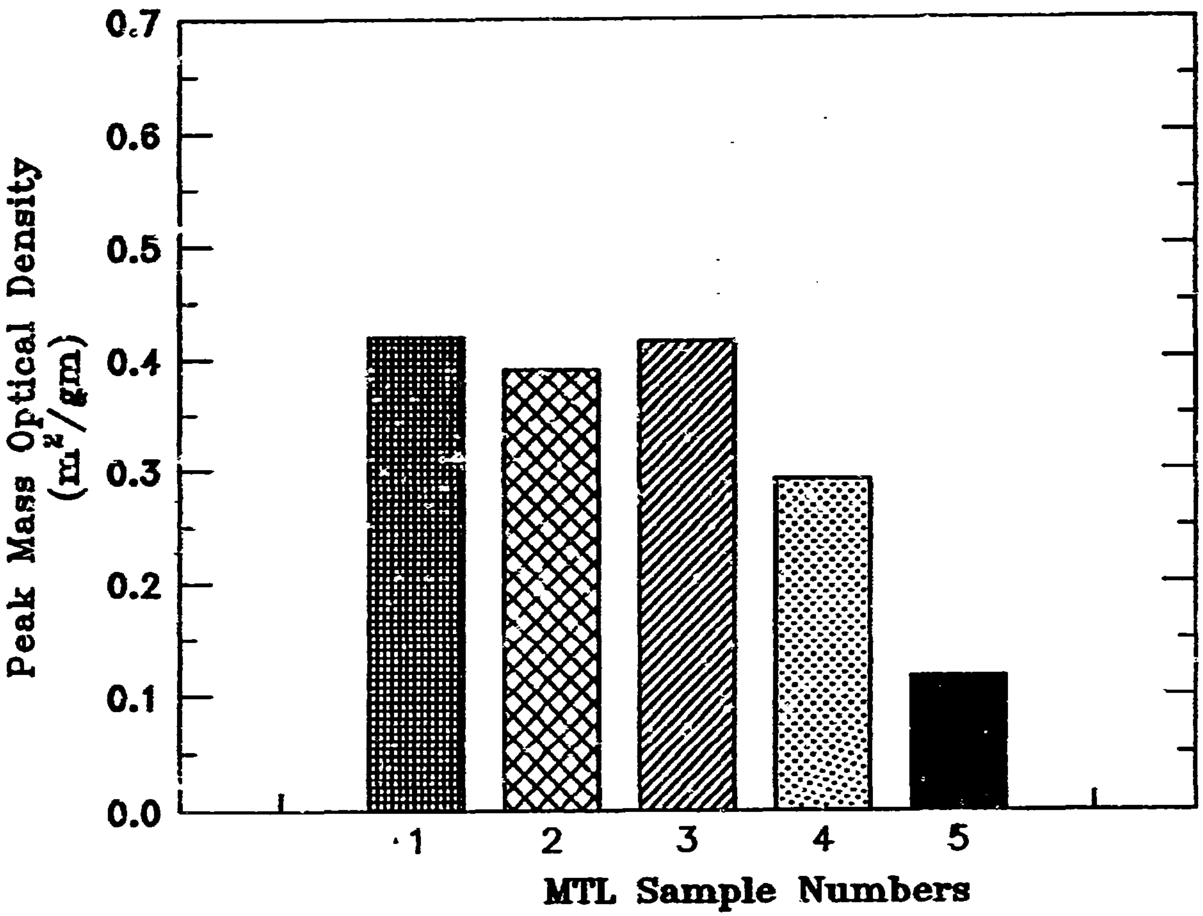

Figure 9. Peak Mass Optical Density of Smoke for the Fiber Reinforced Composite Material Samples.

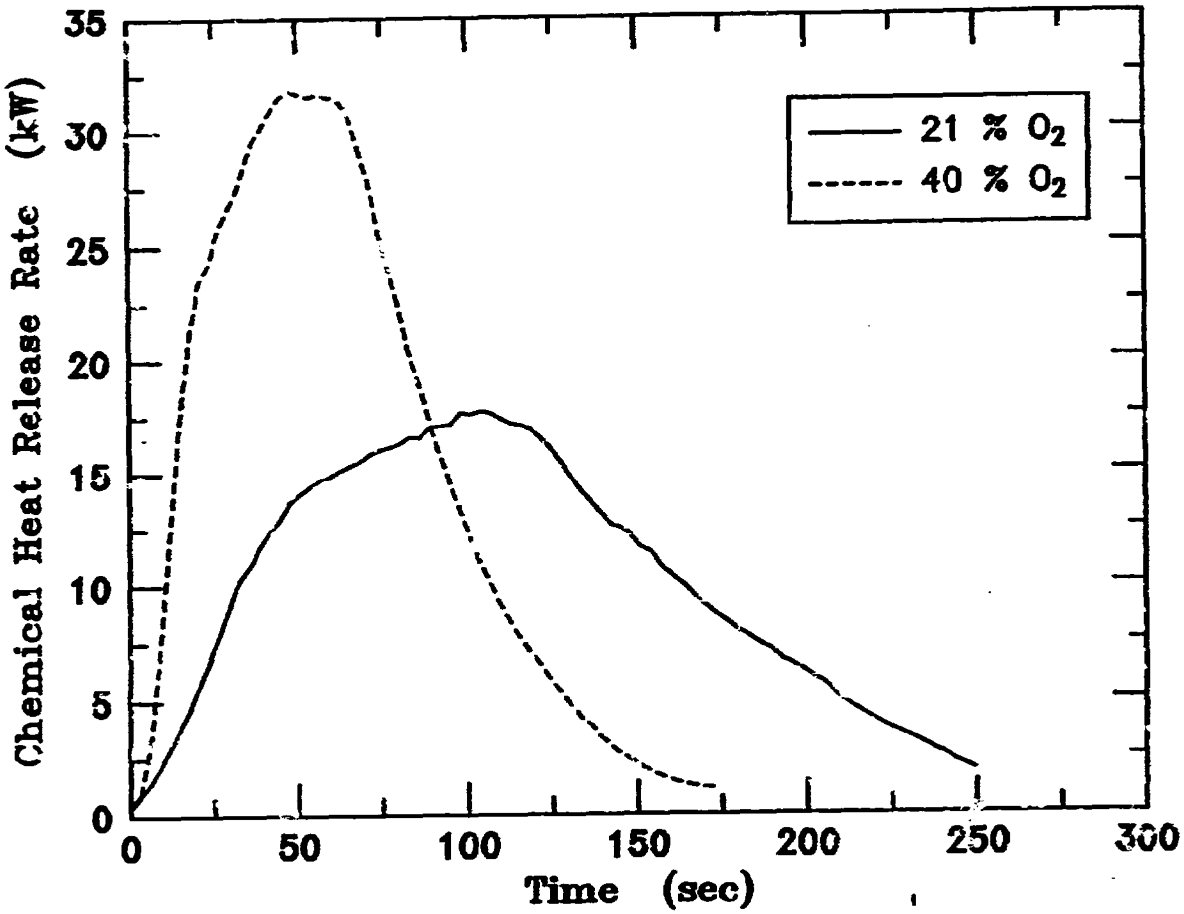

Figure 10. Chemical Heat Release Rate During Fire Propagation for a 0.61 m Long, 0.10 m Wide and 5 mm Thick Vertical Sheet of S-2/Polyester (E-701 Baseline, MTL #1).

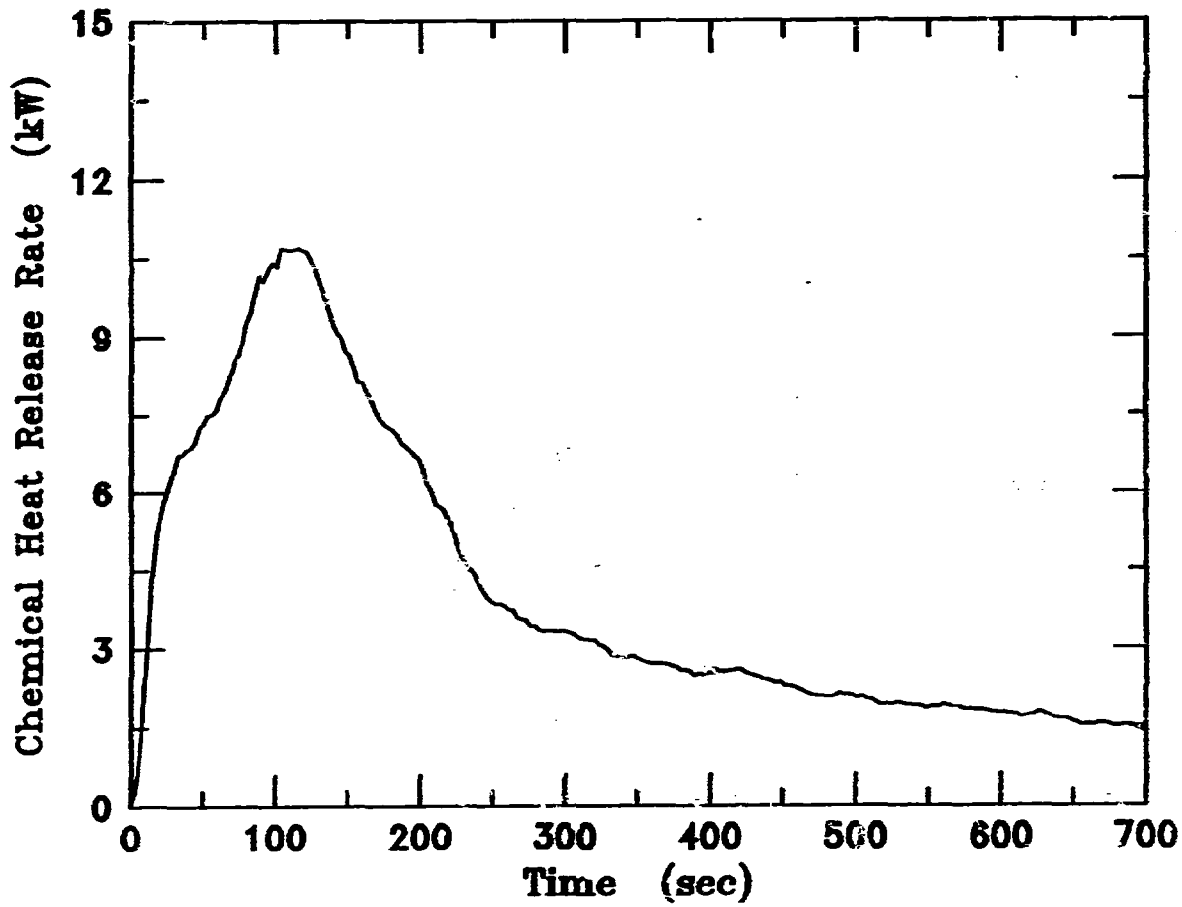

Figure 11. Chemical Heat Release Rate During Fire Propagation for a 0.61 m Long, 0.10 m Wide and 5 mm Thick Vertical Sheet of Kevlar/Phenolic-PVB (Owens-Corning Spall Liner, MTL #4). 40% O_2

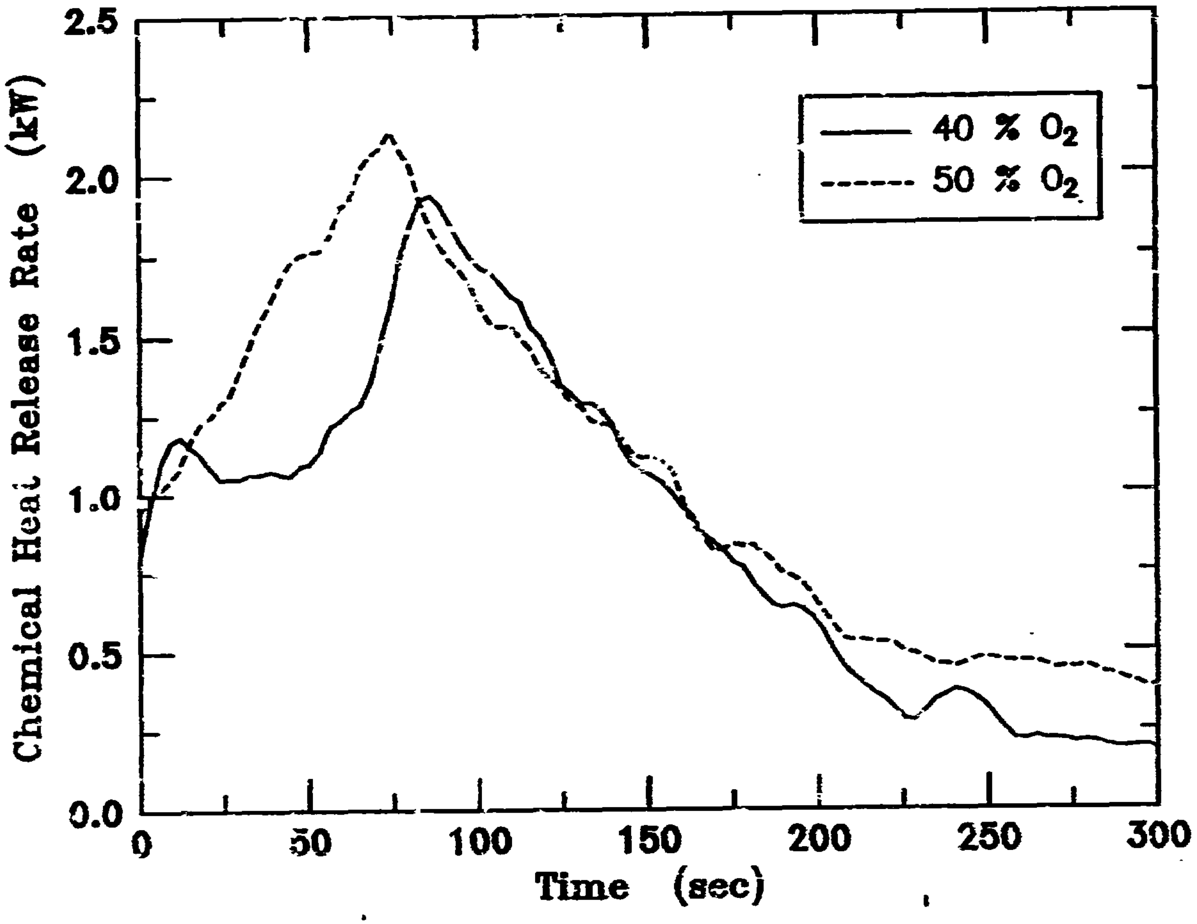

Figure 12. Chemical heat Release Rate During Fire Propagation for a 0.61 m Long, 0.10 m Wide and 3 mm Thick Vertical Sheet of S-2/Phenolic (Owens-Corning, MTL #5).

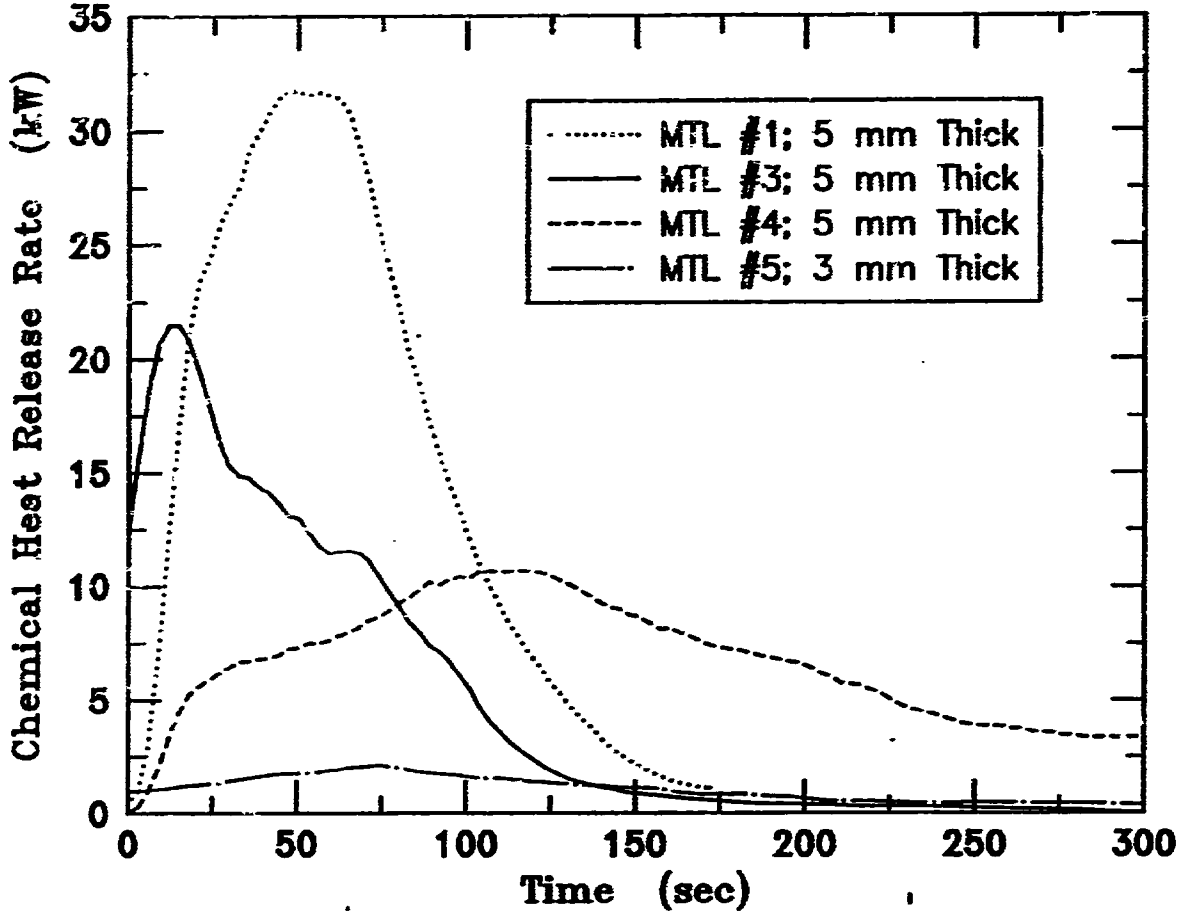

Figure 13. Chemical Heat Release Rate During Fire Propagation for 0.61 m Long and 0.10 m Wide Vertical Sheets of Fiber Reinforced Composite Materials in 40% Oxygen with Bottom 0.20 m of the Sheet Exposed to 50 kW/m^2 of External Heat Flux.

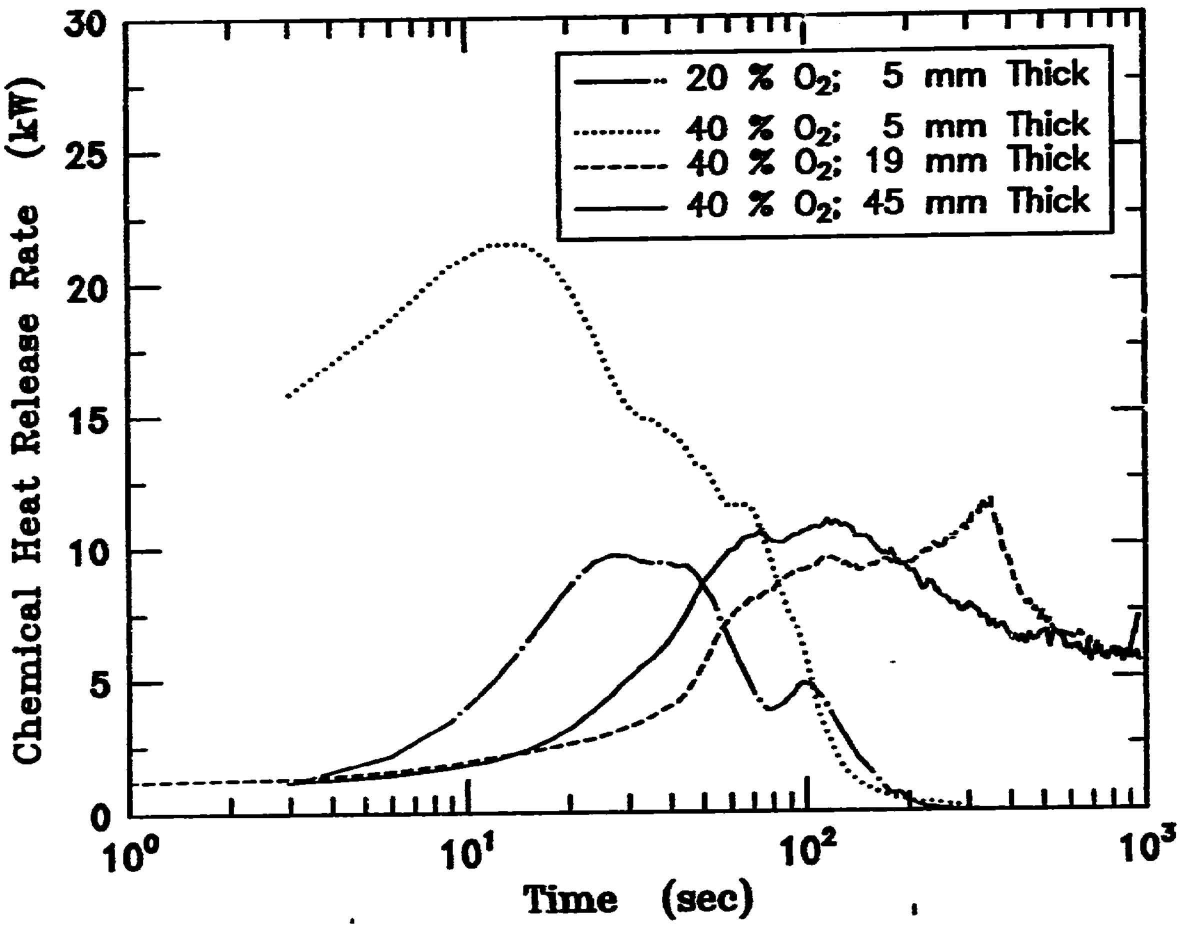

Figure 14. Chemical Heat Release Rate During Fire Propagation for a 0.61 m Long and 0.10 m Wide Vertical Sheet of S-2/Polyester (American Cyanamide Prepreg, MTL #3).

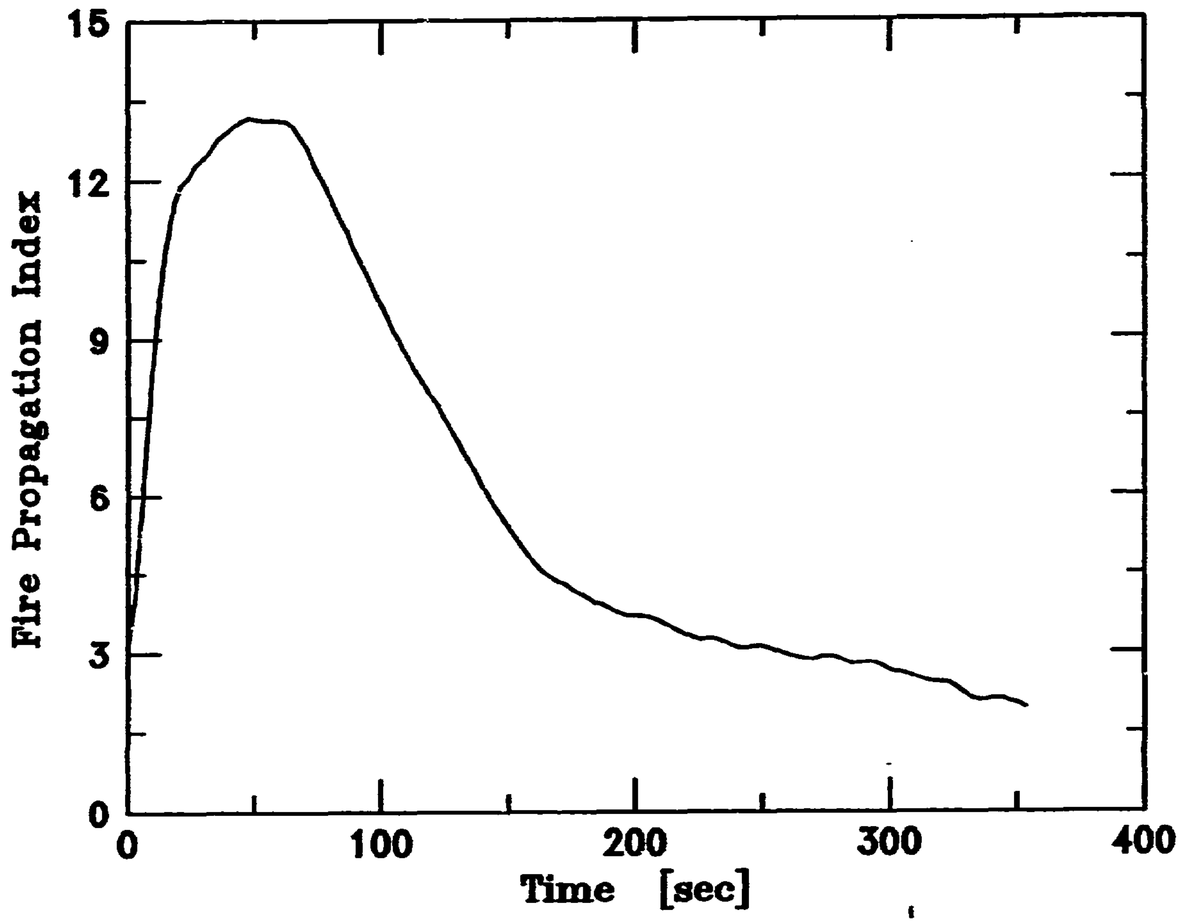

Figure 15. Fire Propagation Index for S-2/Polyester MTL #1 Sample. Vertical Sheet Length: 0.61 m; Width: 0.10 m; Thickness: 4.8 mm; External Heat Flux: 50 kW/m^2; Oxygen Concentration: 40%.

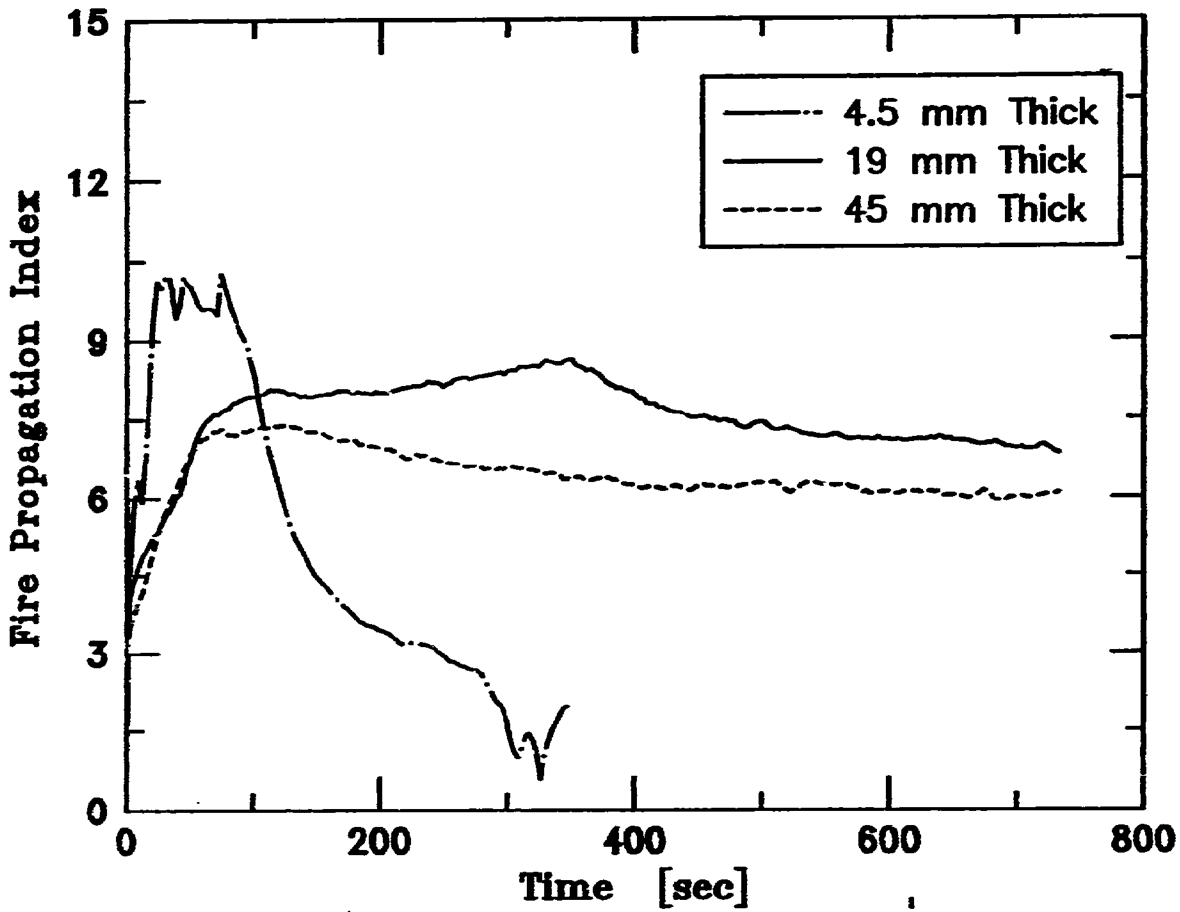

Figure 16. Fire Propagation Index for S-2/Polyester MTL #3 Sample. Vertical Sheet Length: 0.61 m; Width: 0.10 m; External Heat Flux: 50 kW/m^2; Oxygen Concentration: 40%.

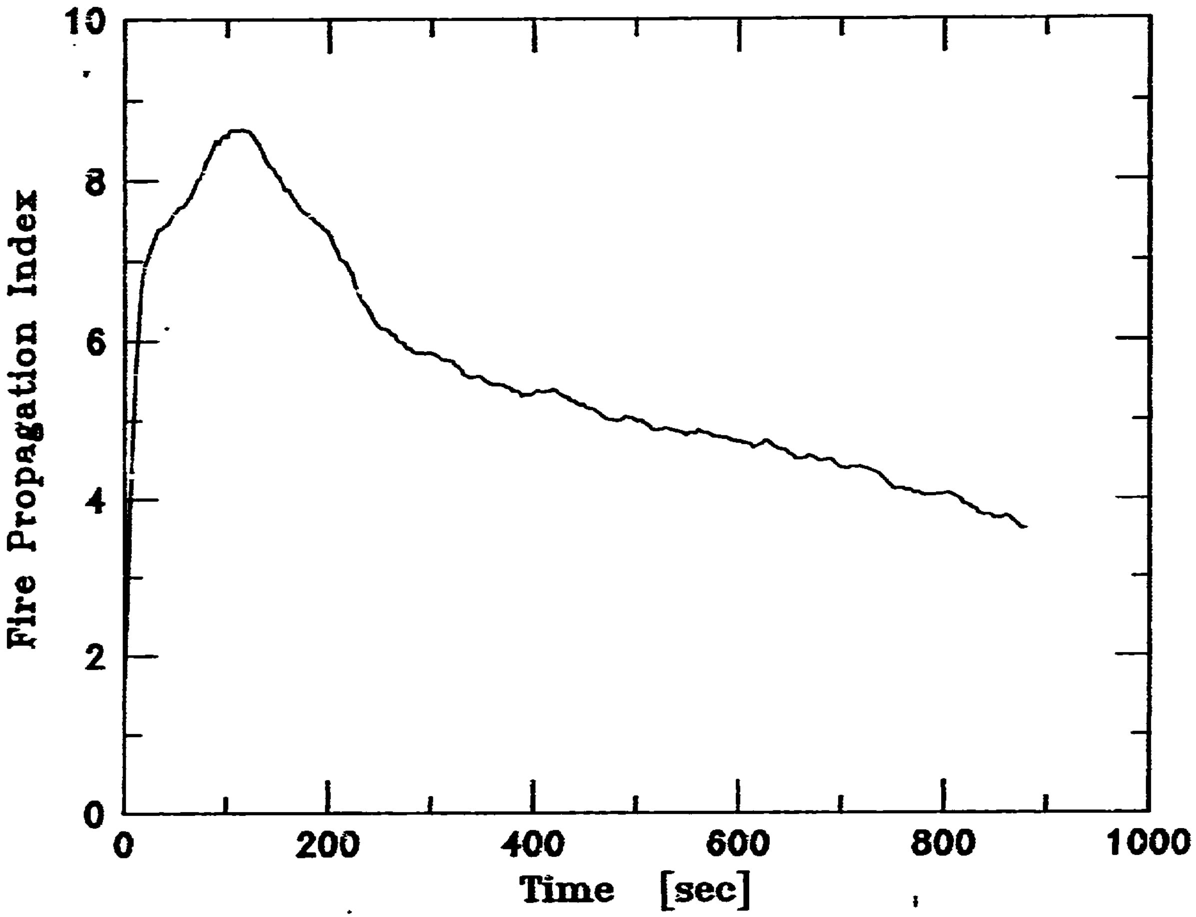

Figure 17. Fire Propagation Index for Kevlar/Phenolic-PVB MTL #4 Sample. Vertical Sheet Length: 0.61 m; Width: 0.10 m; Thickness: 4.8 mm; External Heat Flux: 50 kW/m^2; Oxygen Concentration: 40%.

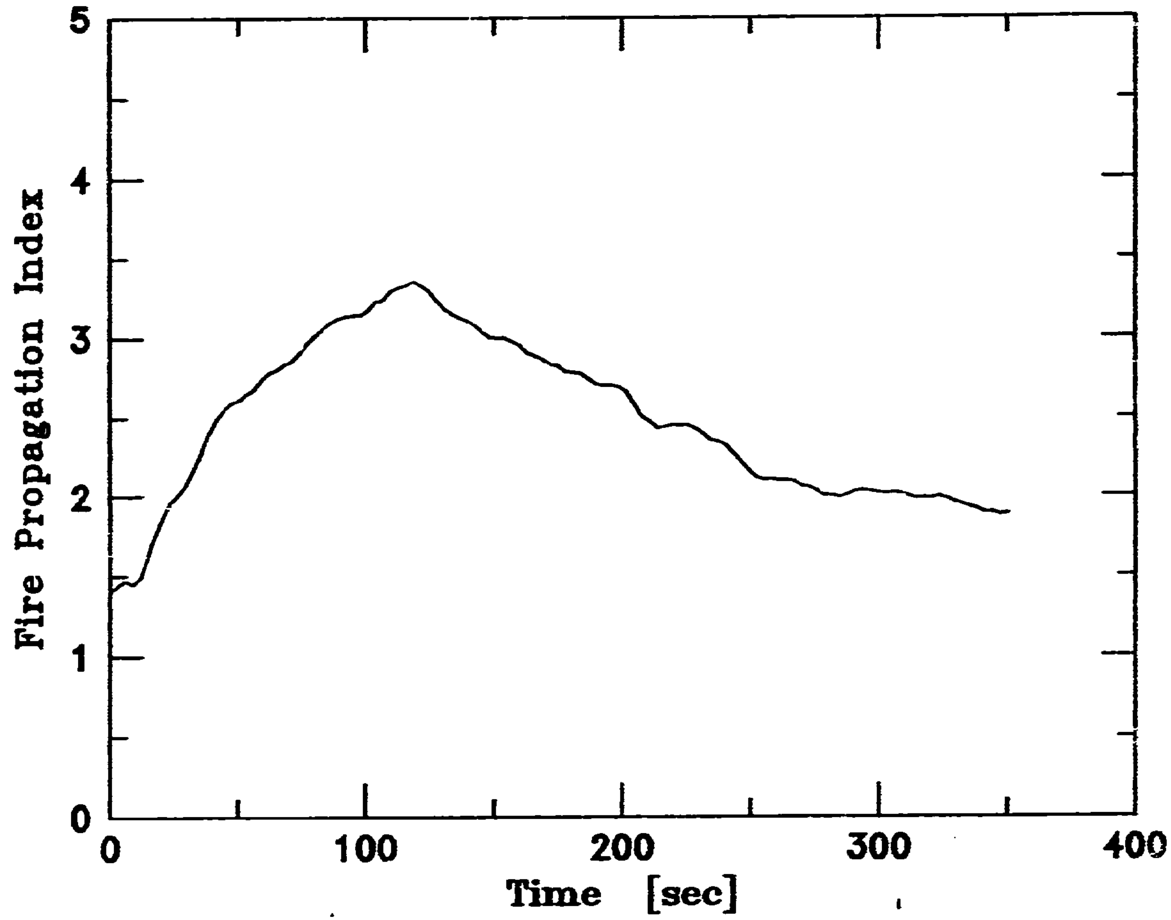

Figure 18. Fire Propagation Index for S-2/Phenolic MTL #5 Sample. Vertical Sheet Length: 0.61 m; Width: 0.10 m; Thickness: 3.2 mm; External Heat Flux: 50 kW/m^2; Oxygen Concentration: 40%.

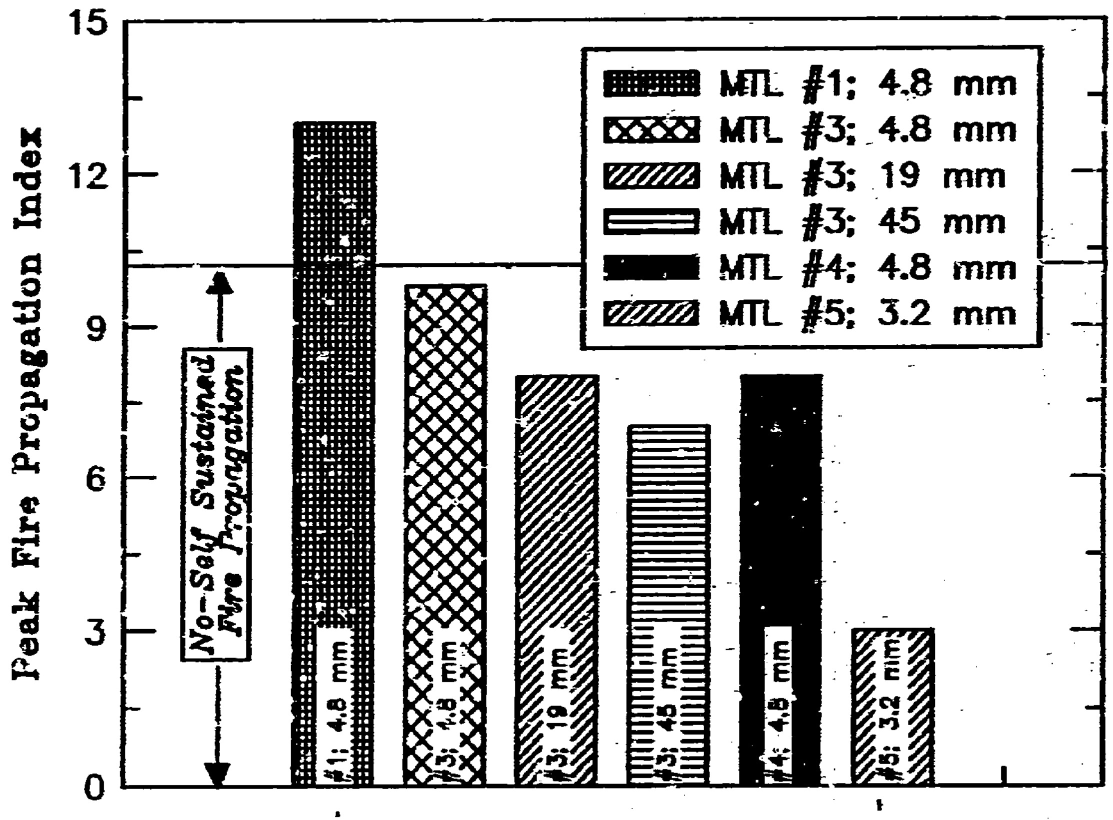

Figure 19. Peak Fire Propagation Index Values for the Fiber Reinforced Composite Material Samples.

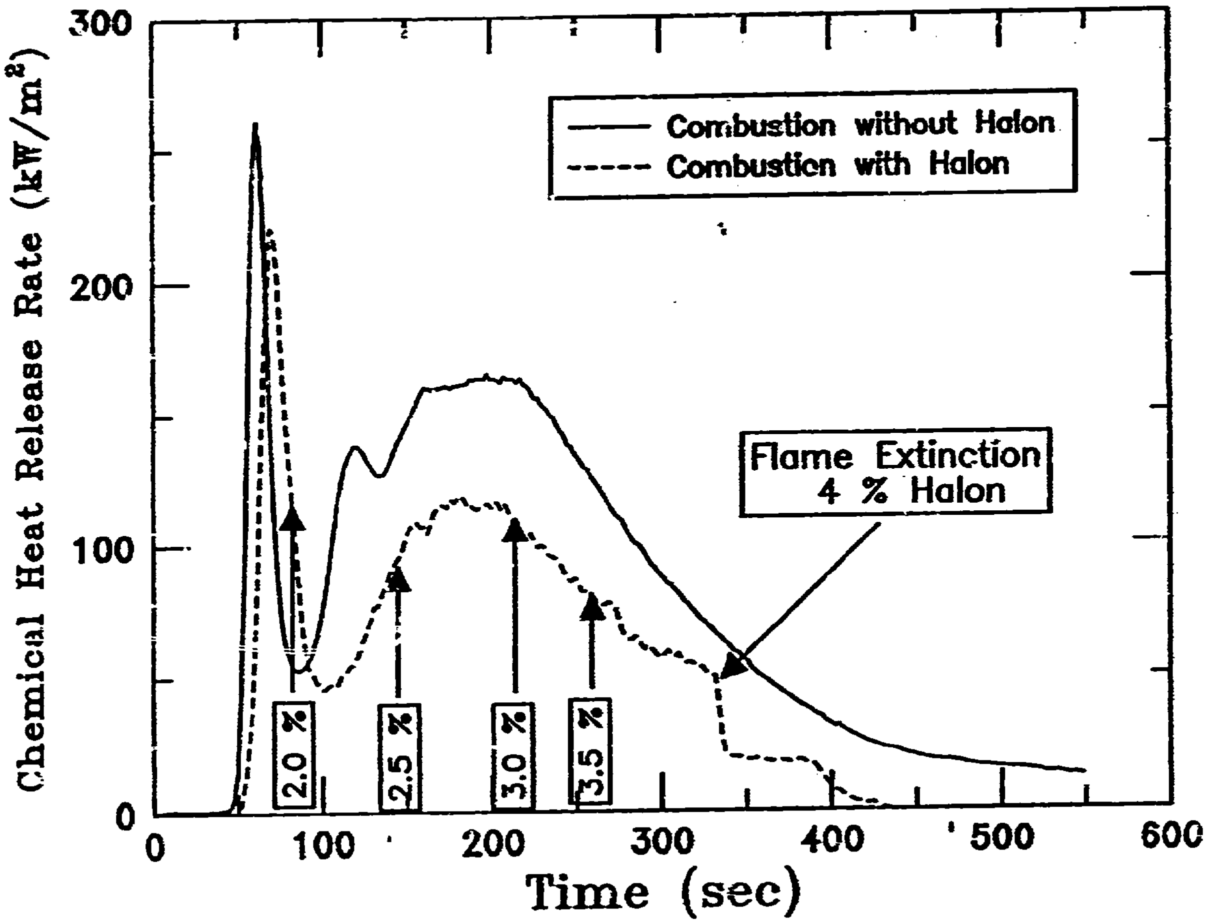

Figure 20. Combustion of MTL #2 Sample in the Presence and Absence of Halon. Sample is Exposed to 60 kW/m^2 of External Heat Flux in Normal Air.

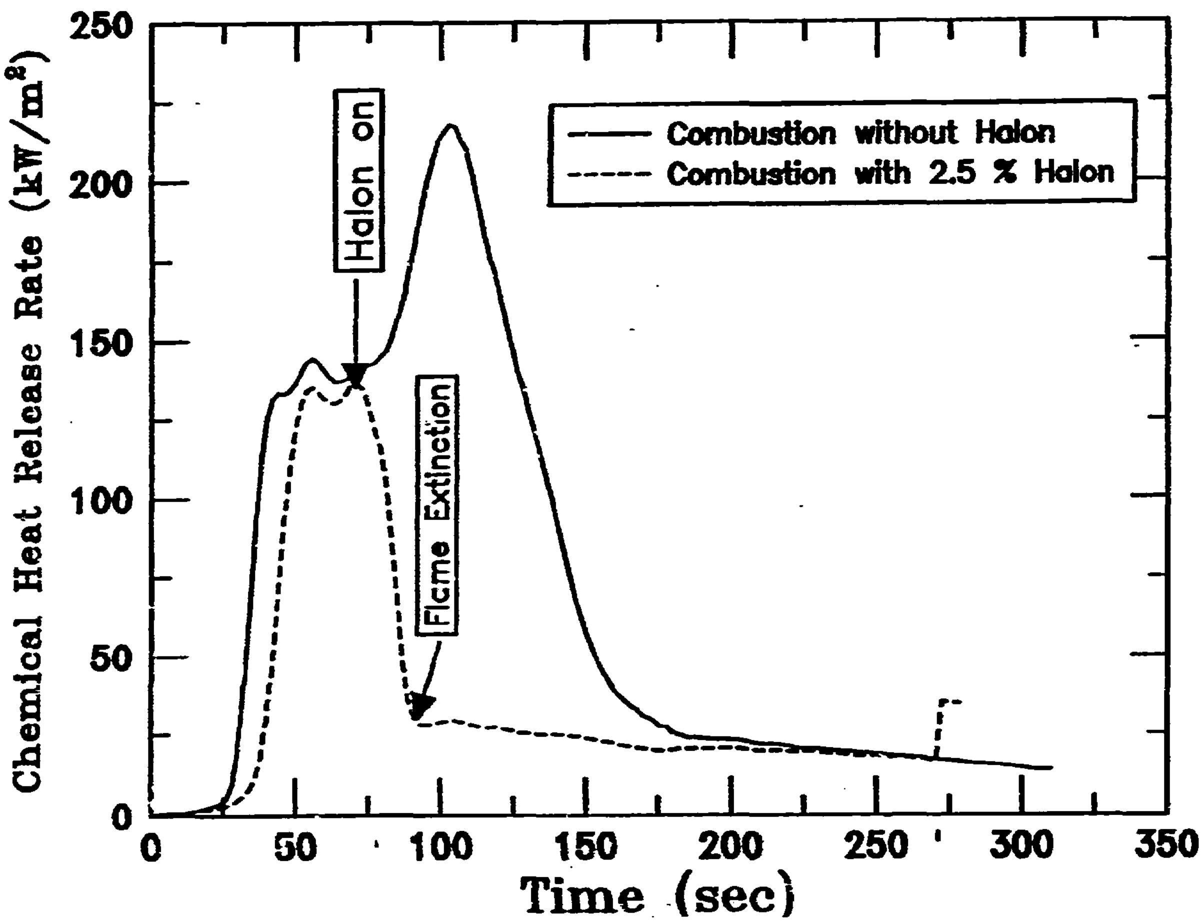

Figure 21. Combustion of MTL #3 Sample in the Presence and Absence of Halon. Sample is Exposed to 60 kW/m^2 of External Heat Flux in Normal Air.

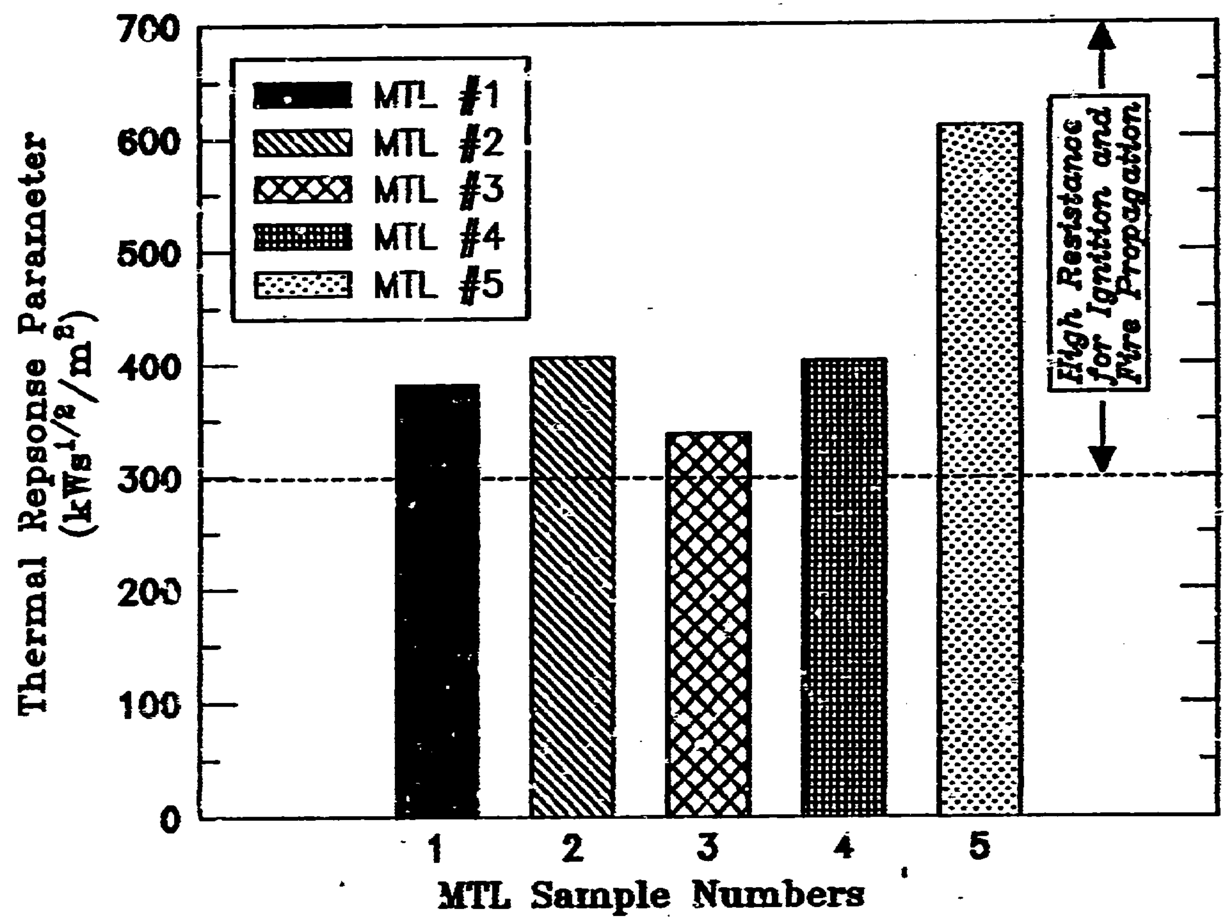

Figure 22. Thermal Response Parameter for Fiber Reinforced Composite Material Samples. (All Samples are 4.8 mm Thick, Except MTL #5 Sample, which is 3.2 mm Thick).

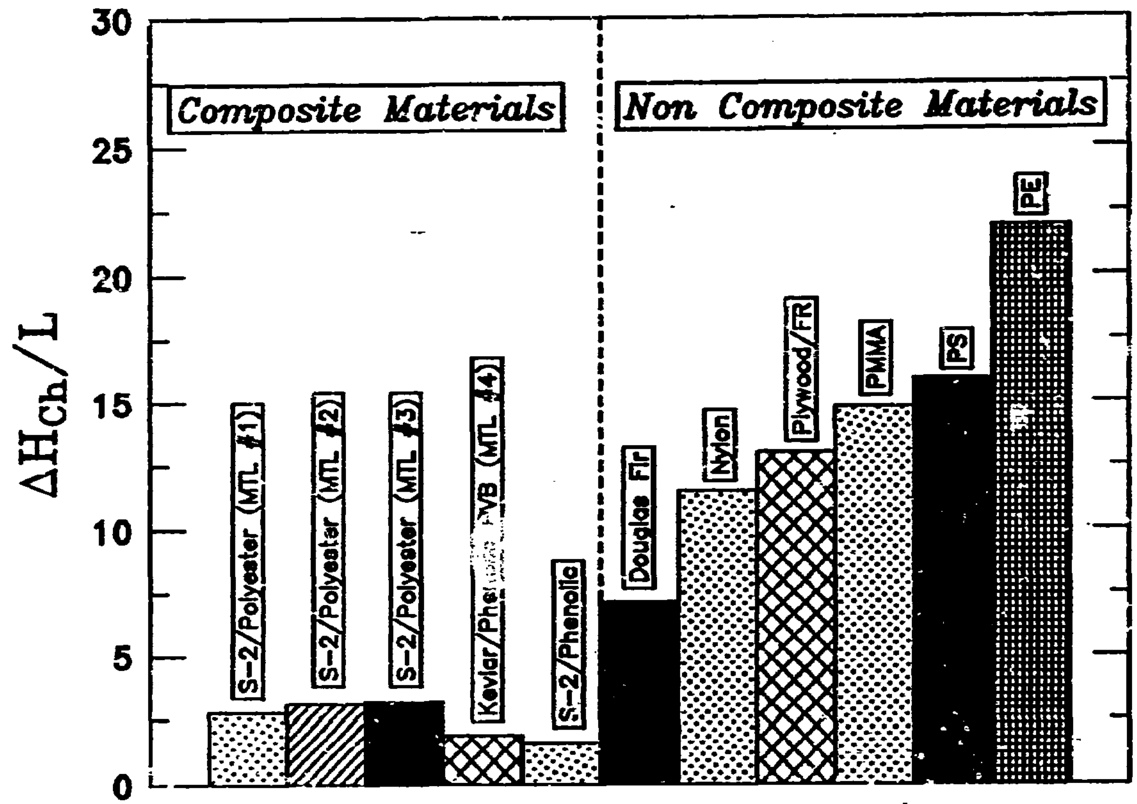

Figure 23. Ratio of the Chemical Heat of Combustion to Heat of Gasification for Fiber Reinforced Composite and Non-Composite Materials.

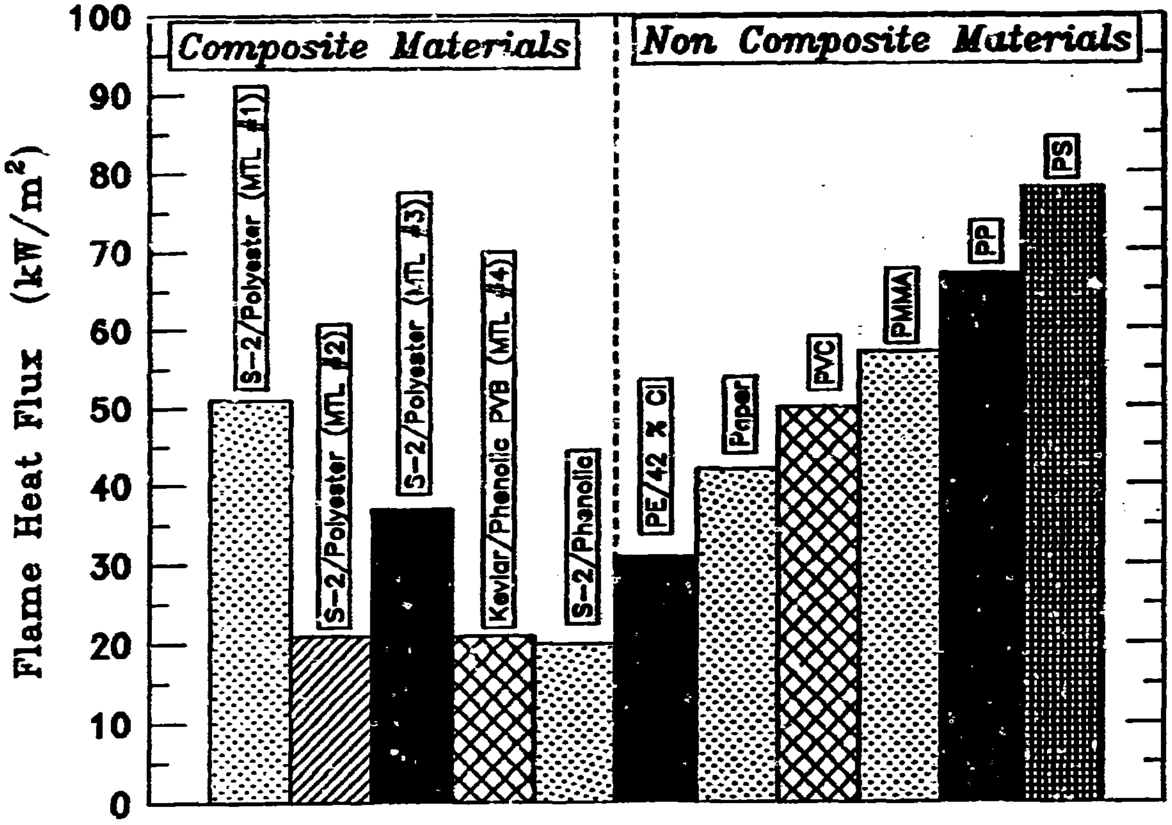

Figure 24. Flame Heat Flux for Fiber Reinforced Composite Materials and Non-Composite Materials Expected in Large Scale Fires.

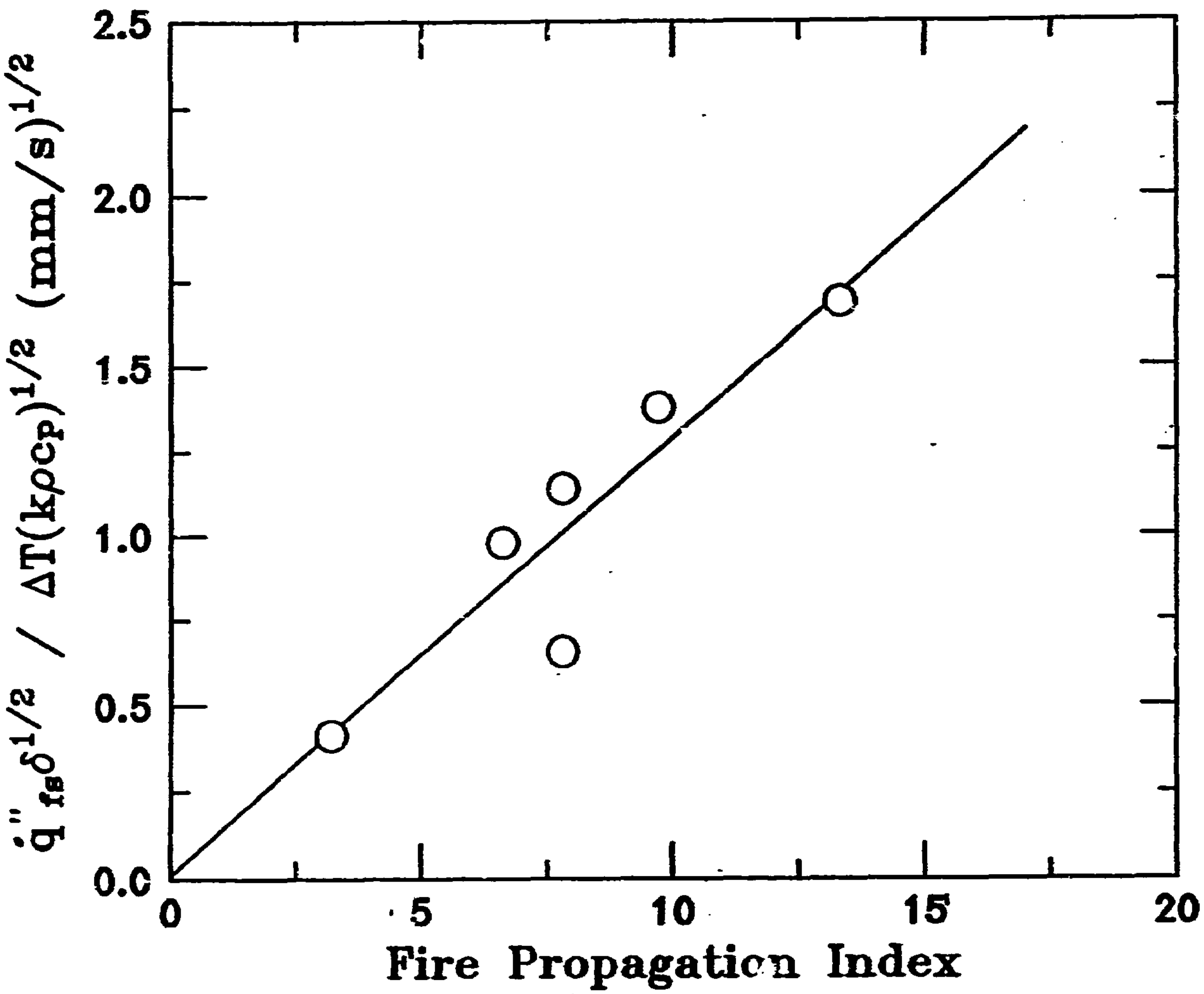

Figure 25. Correlation Between the Rate of Fire Propagation Calculated from the Data in Table III and the Fire Propagation Index from Table IV for the Fiber Reinforced Composite Materials. δ = 0.16 m [4].

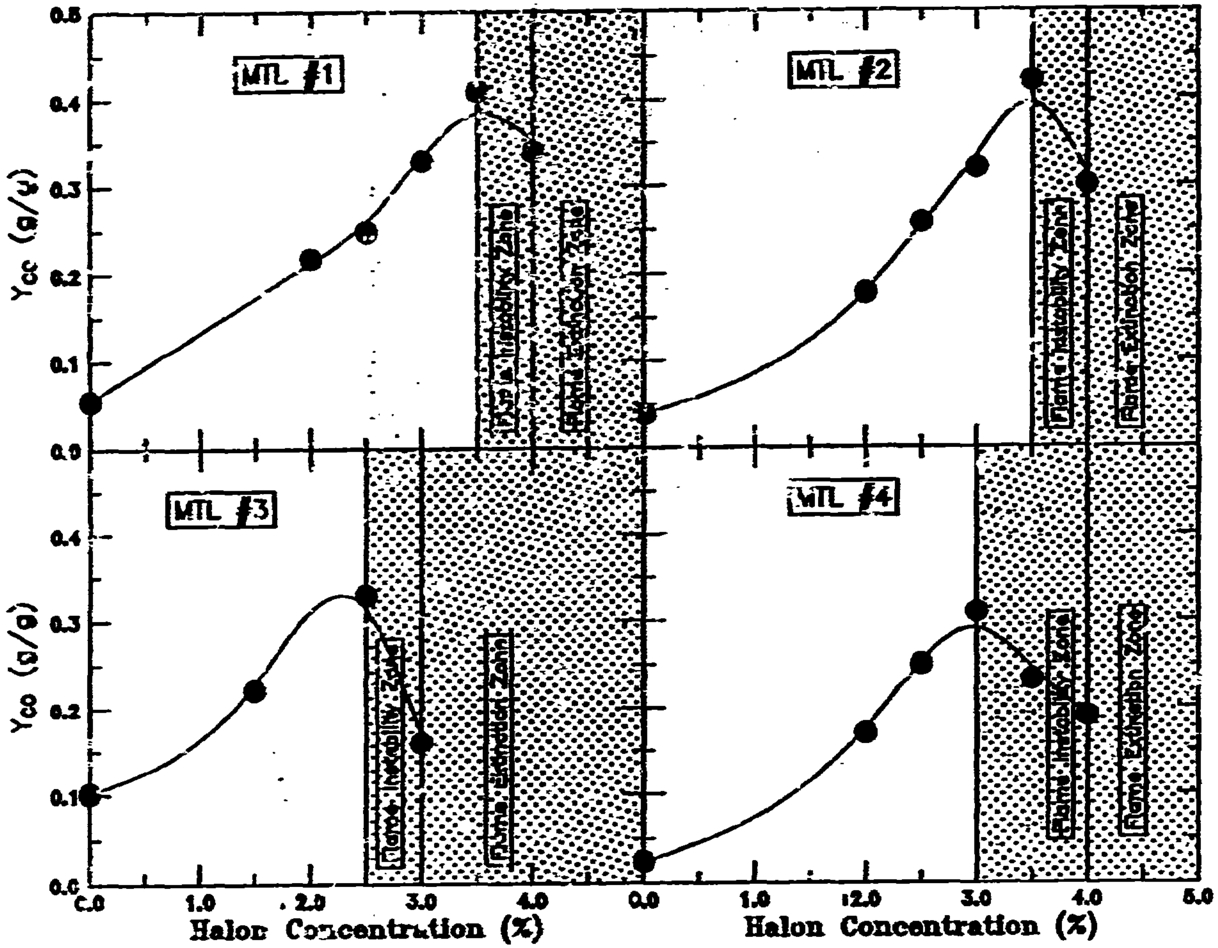

Figure 26. Yield of Carbon Monoxide as a Function of Halon Concentration for the Fiber Reinforced Composite Materials. External Heat Flux of 50 kW/m^2 in Normal Air Was Used in the Experiments.

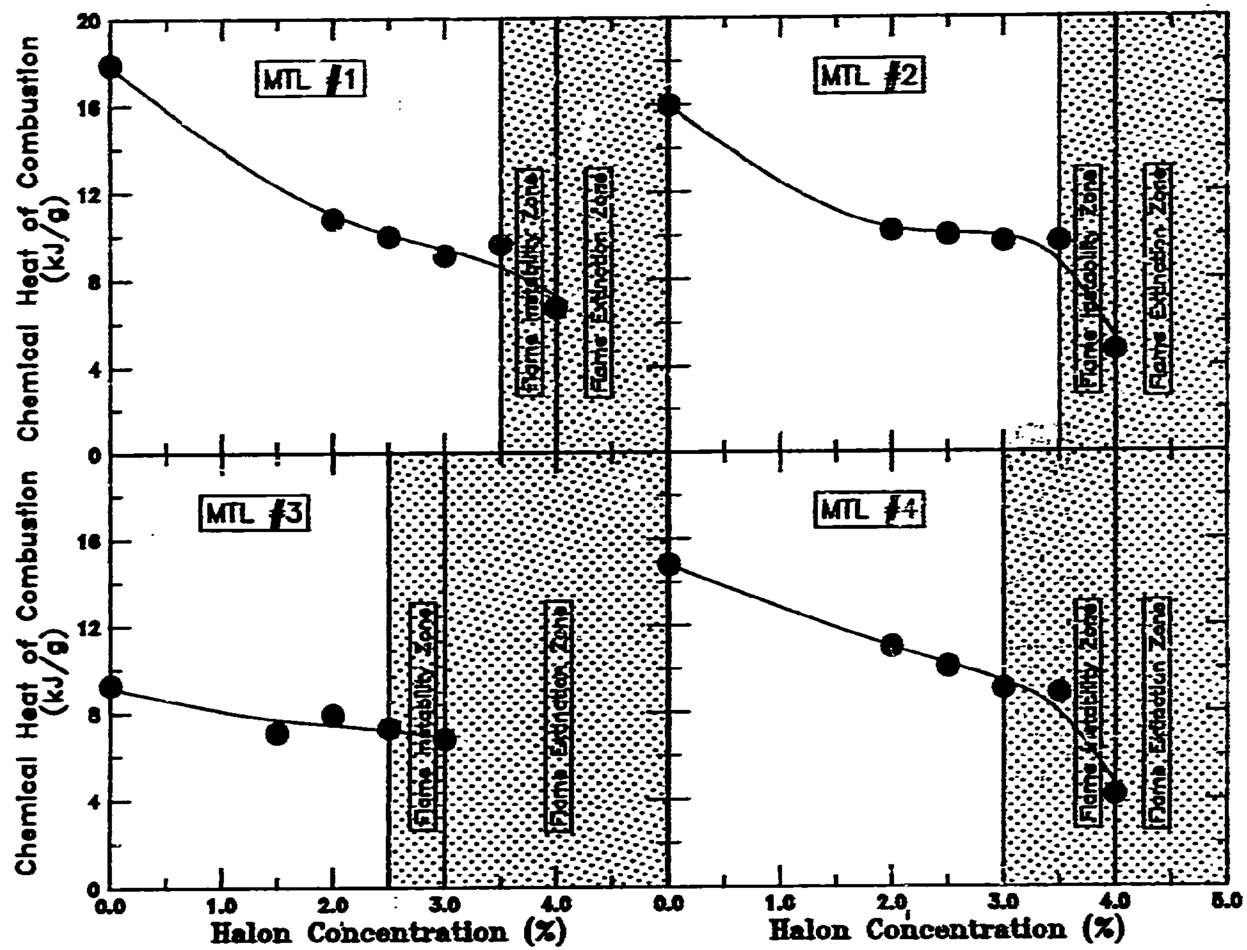

Figure 27. Chemical Heat of Combustion as a Function of Halon Concentration for the Fiber Reinforced Composite Materials. External Heat Flux of 60 kW/m^2 in Normal Air was Used on the Experiments.

APPENDIX
CONCEPTS AND RELATIONSHIPS

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Generation of Material Vapors

The magnitude of heat required to generate vapors from a material depends on the thermal stability of the material. As the temperature or heat flux is increased the generation rate of vapors, measured in terms of mass loss of the material, increases. The following relationship has been found between the mass loss rate and heat flux [2,3]:

$$\dot{m}'' = (\dot{q}_e'' + \dot{q}_f'' - \dot{q}_{rr}'') / L \tag{1}$$

where $\dot{m}''$ is the mass loss rate (g/m^{2}s); $\dot{q}_e''$ is the external heat flux (kW/m^2); $\dot{q}_f''$ is the flame heat flux (kW/m^2); $\dot{q}_{rr}''$ is the surface reradiation loss (kW/m^2) and L is the heat of gasification (kJ/g).

In nonflaming fires, $\dot{q}_f''$ is zero and Eq,. (1) can be expressed as:

$$\dot{m}'' = (\dot{q}_e'' - \dot{q}_{rr}'') / L \tag{2}$$

and in flaming fires, in the absence of external heat flux, $\dot{q}_e''$ is zero and Eq. (1) can be expressed as:

$$\dot{m}'' = (\dot{q}_f'' - \dot{q}_{rr}'') / L. \tag{3}$$

It has been shown that in small-scale experiments with turbulent fires, the flame heat flux approaches its asymptotic value for oxygen concentrations greater than about 30%; the asymptotic value is very close to the value expected in very large fires(7).

A condition where $\dot{q}_e'' + \dot{q}_f'' = \dot{q}_{rr}''$, $\dot{m}'' = 0$, and thus $\dot{q}_{rr}''$ represents the minimum heat flux at or below which the material is not expected to generate vapors. High values of $\dot{q}_{rr}''$ and L and/or low values of $\dot{q}_f''$ are expected to result in small values of $\dot{m}''$, and heat release rates, fire propagation rate, generation rate of smoke, toxic and corrosive fire products are expected to be reduced. Thus, FRC materials with high values of $\dot{q}_{rr}''$ and L and low $\dot{q}_f''$ value would be preferred.

For the assessment of the flammability behavior of FRC materials, it is therefore important to quantify surface reradiation loss, heat of gasification and flame heat flux. For these quantifications, two types of experiments can be performed:

1) Mass Loss Rate as a Function of Temperature

The most commonly used technique is the thermo-gravimetry (TG). Thermogravimetry (TG) is an analytical technique in which the mass of a substance is monitored as a function of temperature or time while the specimen is subjected to a controlled temperature program. The basic components of modern TG have existed since the early part of this century [22-24].

Thermal analysis, in the form of TG, has been employed extensively in the area of polymer flammability to characterize polymer degradation. TG provides a "degradation profile" of a material and permits one to examine and evaluate thermal decomposition which is fundamental to the burning process.

2) Mass Loss Rate as a Function of External Heat Flux

The technique for the measurement of mass loss rate as a function of heat flux was developed in 1976 FMRC using Small-Scale Flammability Apparatus [8]. Several other flammability apparatuses are now available for such measurements, such as OSU Heat Release Rate Apparatus [13] and NIST Cone Calorimeter [14].

Ignition

For thermal thick materials, time to ignition is found to follow the following relationship as external heat flux is varied [4,6]:

$$t_{ig}^{-1/2} \propto \dot{q}''_e / \Delta T (k \rho c_p)^{1/2} , \tag{4}$$

where t_{ig} is time to ignition (s); ΔT is the temperature of ignition above ambient (K); k is the thermal conductivity (kW/m K); ρ is the density (g/m^3) and c_p is the specific heat (kJ/g K). In. Eq. (4), $\Delta T (k\rho c_p)^{1/2}$ is defined as the Thermal Response Parameter (TRP) of the material and expresses the ignition and fire propagation resistance characteristics of the material. Minimum value of $\dot{q}''_e$, at or below which there is no ignition, is defined as the critical heat flux, $\dot{q}''_{cr}$, for ignition [4,6]. The higher the values of $\dot{q}''_{cr}$ and TRP, the greater is the resistance to ignition and fire propagation. Thus, these two parameters need to be quantified for the assessment of resistance to heat exposure. It has been shown that $\dot{q}''_{cr} \approx \dot{q}''_{rr}$ (5).

In the experiments, time to ignition can be measured at various heat flux values and critical heat flux for ignition and TRP can be quantified using techniques such as the one used in the FMRC Small-Scale Flammability Apparatus [4,6].

Heat Release Rate

It has been shown that the heat generated in chemical reactions leading to the generation of CO and CO_2 and depletion of O_2 can be used to calculate the chemical heat release rate using the following relationships [2,3]:

$$\dot{Q}''_{Ch} = (\Delta H_T/k_{CO_2})\, \dot{G}''_{CO_2} + [(\Delta H_T - \Delta H_{CO})/k_{CO}]\, \dot{G}''_{CO} \tag{5}$$

and

$$\dot{Q}''_{Ch} = (\Delta H_T/k_{O_2})\, \dot{C}''_{O_2}, \tag{6}$$

where $\dot{Q}''_{Ch}$ is the chemical heat release rate (kW/m^2); ΔH_T is the net heat of complete combustion (kJ/g); ΔH_{CO} is the heat of combustion of CO (kJ/g); k_{CO} and k_{CO_2} are the maximum possible theoretical yields of CO and CO_2, respectively (g/g); k_{O_2} is the maximum possible mass of oxygen consumed per unit mass of material vapors (mass oxygen-to-fuel stoichiometric ratio) (g/g); $\dot{G}''_{CO}$ and $\dot{G}''_{CO_2}$ are the mass generation rates of CO and CO_2, respectively (g/m^2s); and $\dot{C}''_{O_2}$ is the mass consumption rate of O_2 (g/m^2s).

It has been shown that the convective heat release rate can be calculated using the following relationship [2,3]:

$$\dot{Q}''_{Con} = M\, c_p \Delta T_g / A\ , \tag{7}$$

where $\dot{Q}''_{Con}$ is the convective heat release rate (kW/m^2); M is the total mass flow rate of fire products and air mixture (g/s), ΔT_g is the gas temperature above ambient (K) and A is the total surface area of the material involved in fire (m^2).

The radiative heat release rate is calculated from the difference between the chemical and convective heat release rates [2,3].

It has been shown that heat release rate satisfies the following relationship [2,3]:

$$\dot{Q}_i'' = \Delta H_i \dot{m}'' , \tag{8}$$

where i is chemical, convective or radiative and ΔH_i is the heat of combustion (kJ/g).

From Eqs. (1) and (8):

$$\dot{Q}_i'' = (\Delta H_i/L)\ \dot{q}_n'' , \tag{9}$$

where $\dot{q}_n''$ is the net heat flux defined as:

$$\dot{q}_n'' = \dot{q}_e'' + \dot{q}_f'' - \dot{q}_{rr}'' . \tag{10}$$

ΔH_i in Eqs. (8) and (9) can be expressed as $\chi_i\ \Delta H_T$, where χ_i is the combustion efficiency. Eq. (9) can be expressed as

$$\dot{Q}_i'' = \chi_i\ (\Delta H_T/L)\ \dot{q}_n'' . \tag{11}$$

In Eq. (11), $\Delta H_T/L$ is a fundamental physicochemical property of the material. ΔH_T can be measured in the Oxygen Bomb Calorimeter or can be calculated from the heat of formation, and values of L can be obtained from experiments described previously. The value of χ_i depends on the chemical structure of the material and fire ventilation, but not on fire size for turbulent fires. For conditions where $\dot{q}_e'' >> \dot{q}_{rr}''$, Eq. (11) can be expressed as:

$$\dot{Q}_i'' = \chi_i\ (\Delta H_T/L)\ \dot{q}_e'' . \tag{12}$$

Thus, experiments can be performed where the chemical, convective and radiative heat release rates can be measured at various external heat flux values. Linear relationships should be found for the experimental data for higher $\dot{q}_e''$ values as suggested by Eq. (12) and $(\Delta H_i/L)$ and χ_i (if ΔH_T is known) can be determined. Materials with low values of $\Delta H_i/L$ (and χ_i) are expected to have low heat release rates. Several apparatuses are available to

quantify heat release rates: 1) the FMRC Small-Scale Flammability Apparatus where chemical, convective and radiative heat release rates are measured [2-10]; 2) the OSU Heat Release Rate Apparatus [(13] where only convective heat release rate is measured, and 3) the NIST Cone Calorimeter [14] where only chemical heat release rate is measured.

Fire Propagation

It has been shown that the fire propagation behavior can be quantified using a Fire Propagation Index (FPI) [4,6]. FPI is expressed as the ratio of the radiative heat release rate to the thermal response parameter (TRP),

$$FPI = [(x_R \dot{Q}'_{Ch})^{1/3} / TRP] \times 1000 , \tag{13}$$

where $\dot{Q}'_{Ch}$ is the chemical heat release rate per unit width or circumference of the sample (kW/m), and x_R is the radiative fraction of the chemical heat release rate, assumed to be constant and equal to 0.40. FPI is quantified by measuring $\dot{Q}'_{Ch}$ as a function of time during fire propagation and by measuring TRP in separate ignition experiments.

FPI can be considered as a quantity proportional to the square root of the rate of fire propagation ($v^{1/2}$). For concurrent flow for thermally thick solids, v is expressed as [4]:

$$v^{1/2} \approx \dot{q}''_f \delta_f^{1/2} / \Delta T (k\rho c_p)^{1/2}, \tag{14}$$

where v is m/s; $\dot{q}''_f$ is the flame heat flux (kW/m^2); and δ_f is the effective flame heat transfer distance estimated to be about 0.16 m in our apparatus (4); it has been shown that [7],

$$\dot{q}''_f \propto m_{o_2} \quad (15)$$

where m_{o_2} is mass fraction of oxygen. Thus, $v^{1/2}$ can be calculated from the fundamental flammability data and is expected to correlate with the FPI values of various materials.

Generation of Smoke, Toxic and Corrosive Fire Products

Smoke, toxic and corrosive products are generated in fires as a result of vaporization, decomposition and combustion of materials in the presence or in the absence of air.

It has been shown that the generation rate of fire products satisfies the following relationship [2,3]:

$$\dot{G}_j'' = Y_j \, \dot{m}'' \, , \tag{16}$$

where $\dot{G}_j''$ is the generation rate of product j (g/m^{2}s) and Y_j is the yield of the product (g/g). From Eqs. (1), (10) and (17):

$$\dot{G}_j'' = (Y_j/L) \, \dot{q}_n'' \, . \tag{17}$$

Y_j in Eq. (17) can be expressed as $f_j \, k_j$, where f_j is the generation efficiency of the product, as:

$$\dot{G}_j'' = f_j \, (k_j/L) \, \dot{q}_n'' \, . \tag{18}$$

k_j/L is a fundamental physicochemical property of the material. k_j can be calculated from the elemental composition of the material, which can be measured using microanalytical techniques. f_j depends on the chemical structure of the material and additives and fire ventilation, but not on fire size for turbulent fires. In order to determine Y_j and f_j, experiments can be performed, where generation rates of individual fire products are measured, at various external heat flux values. Linear relationships should be found from the experimental data for higher $\dot{q}_e''$ values as indicated by Eqs. (17) and (18) and (Y_j/L) and f_j (if k_j value is known) can be determined. Materials with low values of Y_j/L (and f_j) are expected to have low values for the generation rates of fire products. Several apparatuses are available for such quantifications such as the FMRC Small-Scale Flammability Apparatus [2-10, 17, 18], the OSU Heat Release Rate Apparatus [13] and the NIST Cone calorimeter [14]. For detailed examination of the fire products, pyrolysis-gas chromatography/mass spectrometry (Py-GC-MS) techniques [16] can be used.

Generation rate of smoke can be quantified by measuring the mass of smoke and/or the optical density of smoke, D, defined as:

$$D = (1/\ell) \log_{10} (I_o/I) , \qquad (19)$$

where ℓ is the optical path length (m) and I/I_o is the fraction of light transmitted through smoke. Since D depends on the generation rate of smoke and total flow rate of the fire product-air mixture, D is expressed as the mass optical density (MOD) in m^2/g [17]:

$$MOD = (1/\ell) [\log_{10} (I_o/I)] \dot{V}/\dot{m}'' A , \qquad (20)$$

where $\dot{V}$ is the total volumetric flow rate of the fire product-air mixture (m^3/s).

Techniques have been developed to quantify corrosive properties of the fire products [17] as well as the toxic properties using animals [19]. Toxicity evaluation tested on identified species can also be made by comparisons with the information available from the NIOSH Registry of Toxic Effects of Chemical Substances.

Fire Extinguishment

The efficiency of fire extinguishment depends on the rate of agent application and the ability of the agent to interrupt the chemical reactions responsible for generating heat in the gas phase or removing heat from the surface of the burning material. No small-scale techniques are available for quantifying fire extinguishment; however, recently an attempt has been made to develop them using the FMRC Small-Scale Flammability Apparatus [21].

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A. Tewarson
Factory Mutual Research Corporation
Norwood, Massachusetts 02062

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Fiber reinforced composite (FRC) materials are used extensively because of their physicochemical properties and high strength-to-weight ratio. The objective of the study was to assess the flammability characteristics of FRC materials using small-scale experiments. Five FRC samples (about 3 to 45 mm in thickness) were examined. Results showed that FRC materials have high resistance to ignition, a high heat of gasification and a low Fire Propagation Index (FPI), indicating that self-sustained fire propagation is expected to be difficult for these materials (fires are not expected to propagate beyond the ignition zone). Thus, these results suggest that a composite combat vehicle, by virtue of its construction, would not necessarily present as severe a fire hazard as ordinary combustibles.

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